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AN ACOUSTIC DATA-PROCESSING SOFTWARE PACKAGE FOR THE STATISTICAL ANALYSIS OF ARRAY BEAM-NOISE AND NOISE DIRECTIONALITY ESTIMATION

R.A. WAGSTAFF, D.J. KEWLEY and P.S. KEAYS

MARITIME SYSTEMS DIVISION
WEAPONS SYSTEMS RESEARCH LABORATORY

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AN ACOUSTIC DATA-PROCESSING SOFTWARE PACKAGE FOR THE STATISTICAL ANALYSIS OF ARRAY BEAM-NOISE AND NOISE DIRECTIONALITY ESTIMATION

R.A. Wagstaff*, D.J. Kewley and P.S. Keays

SUMMARY (U)

A software package for onboard acoustic data-processing and the statistical analysis of array beam-noise has been implemented on an IBM 3033 computer system. The package both assesses data quality and measures the noise-field's statistical characteristics and directionality. Many of the outputs are sufficiently general to have application to other types of data or to satisfy other objectives. The various outputs are described and illustrated by results from measurements of the ambient noise by a towed array. A simplified run procedure is included to facilitate the use of the software package by the analyst.

* Short term visitor from US Naval Ocean Research and Development Activity, NSTL Station, Mississippi, USA. (November 1985)

Author's address:
Maritime Systems Division
Weapons Systems Research Laboratory
PO Box 1700
Salisbury, 5108
South Australia

Requests to:
Chief, Maritime Systems Divsion
Weapons Systems Research Laboratory
PO Box 706
Darlinghurst, 2010
New South Wales

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1. INTRODUCTION

Over a period of several years, experience gained through participation in measurement exercises and the resulting data analyses has led to the development of a "standard" software package for onboard statistical analysis of time-series data. Although in the past, the data have been of beam-noise acquired by towed arrays, many of the products are sufficiently general to apply to data acquired by other systems, even a single hydrophone. The purpose of this report is to describe the capabilities and products of this software package. This package is called the Towed Array Noise Analysis Package (TANAP).

The software package was developed with two goals in mind. The first was to enable an assessment of measurement system performance and data quality. This requires routines that can address the performance of the sonar system as a measurement tool and others that can assess the character of the ambient-noise field at the time of the measurement. In other words, how did the condition of the measurement tool affect the measurements, and was the noise-field sufficiently "well behaved" to enable meaningful results to be obtained? The second objective was to provide products that could be useful in the characterization and the analysis of the noise-field. Some products satisfy both purposes but are discussed only once. Some, such as the mean level, are commonly used and need little or no explanation, so that the discussions of them are appropriately brief. For less well-known products, the discussions are sufficient to give only an idea of their form, utilization, and utility; more thorough discussions can be obtained from the references.

Section 2 of this report discusses the input data requirements of this software package. Section 3 discusses the statistics and products generated that are useful for assessing measurement system performance and data quality. Section 4 discusses the statistics and products generated that are useful to analyse and describe the noise-field and the beam-noise data.

Finally, Appendix I contains a brief description of the programs and subroutines in the beam-noise processing software and Appendix II gives an example of a simplified run procedure.

2. PRELIMINARY DATA PROCESSING AND OVERVIEW

The experimental procedure by which the data are collected and analysed is as follows. Long duration (2 to 12 h) tows are made on one heading to acquire data to determine the statistics of towed-array beam-noise. Data are also collected while on various array headings (called a noise polygon) to obtain estimates of noise-field spatial statistics, ie, noise-field horizontal directionality.

The data from each hydrophone are time sampled and processed by a Fast Fourier Transform (FFT) to get time-series of frequency spectra for each hydrophone. The spectral data for all hydrophones for each time increment are then processed by an FFT across the array (with zero filling to be a power of 2) to get beam-noise in each spectral bin. This procedure is illustrated in figure 1 for an array of 40 hydrophones. The resulting spectrum analysed beam-noise time-series of complex Fourier beam-noise coefficients are stored on disk and are the input data to the beam-noise processing and analysis software.

The data-processing system has two purposes. The first purpose is to produce information (called "quality-assessment products", and described in Section 3) with which to assess the acoustic performance of the measurement system and to determine whether the acoustic field is sufficiently well-behaved to yield

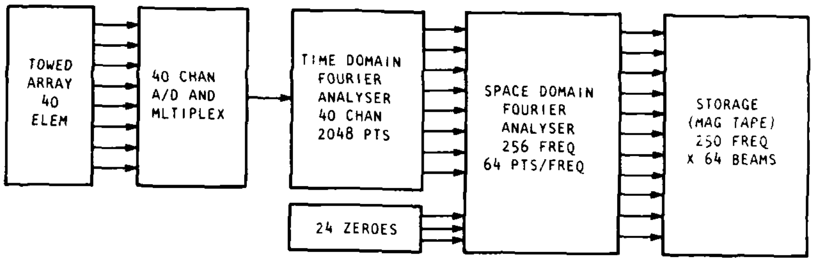


Figure 1. Data processing and reduction

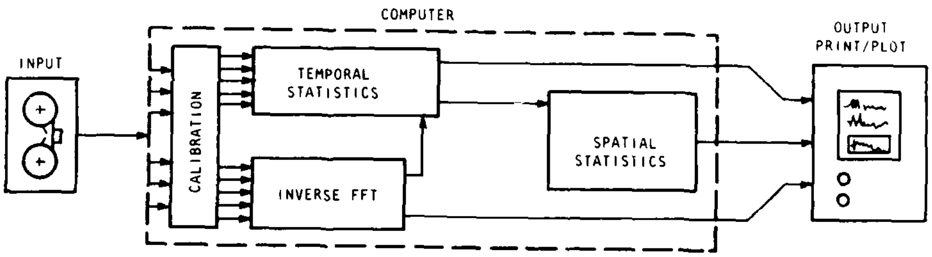


Figure 2. The data-acquisition, processing, and analysis system

meaningful results, ie, to assess the quality of the data. The second purpose is to produce and display statistical parameters (called "analysis products", and described in Section 4) that can provide estimates of the temporal and spatial statistics of the noise-field (or, more accurately, of the influence of the noise-field on the acoustical output of the array). Some of the data-processing products serve for both assessment and analysis.

Table 1 lists the data-processing products in the order of their appearance. The table shows whether they are used primarily for quality assessment or for analysis, or for both. It also lists the figures used as examples in Chapters 3 and 4.

The first step in the data-processing (see figure 2) is to apply the calibration corrections. This produces ambient-noise levels in dB//μPa^2/Hz. An inverse FFT is then applied to the calibrated beam-noise data to provide calibrated hydrophone data. When a strong signal is present these data can be used to calculate the phase angle across the array relative to a common hydrophone and normalized for the direction of the source and plotted versus hydrophone number (see figure 4).

Statistical calculations for each time-series are then undertaken (see figure 5 in Section 3 below). These calculations are performed on all beams including the virtual beams (ie, those formed by the FFT beamformers that correspond to phase shifts greater than that for an endfire beam) and on two hydrophones: the one with the median noise level and another selected for comparison. The results of these statistical calculations provide the rest of the data-processing products (see figures 3, 5, 6, and 7 in Section 3 and figures 8, 9, 10, 11, 12, and 13 in Section 4). The ways in which these products are used for assessing the data quality or for analysing the noise-field are discussed below in Sections 3 and 4 respectively.

3. ASSESSMENT OF TOWED ARRAY SYSTEM'S PERFORMANCE AND DATA QUALITY

The measured data are the basic foundation on which rests the interpretation of results and formulation of conclusions. When the quality of the data is low or uncertain, the level of confidence in the correct interpretation of the results and formulation of conclusions must also be low. Data quality can be a severe problem when the phenomenon being measured is as highly variable as ambient noise. The severity is compounded when the measurement system is a towed line array, which always has its own interfering source (towship) and is not constrained to remain linear, horizontal, or on a given heading.

The current ability of the data-processing system to evaluate and filter out self-noise is assessed before starting the measurements at a site. This procedure is described below in Section 3.1. After the measurements have been obtained and before they are analysed, their quality is evaluated. This procedure is described below in Section 3.2. Both procedures make use of the data-processing products listed in Table 1.

3.1 Products

The products and statistics which are used to assess the measurement system's performance and the quality of the data are listed below:

(a) To indicate contaminating sources or poor beamforming

Listings of the average noise-power levels, the geometric mean intensity levels, and the differences between them. Single listings for each analysis frequency in each time-period, as shown in the AVGPR, AVG and PRDIF columns in figure 5, and plotted as in figures 3(a) and 3(b) for hydrophones and beams respectively.

(b) To indicate an erratic beamformer or hydrophone output

Standard deviations of all beams and two hydrophones. Single listing for each analysis frequency in each time-period, as shown in the STDEV column in figure 5 and as plotted in figure 3. The beam numbers on the outsides of the vertical dashed lines correspond to virtual beams. The utility of the virtual beams for system performance and data quality assessment is discussed later in this section.

(c) To indicate faulty hydrophone channels or irratic beamforming

The median and average phase angle for all hydrophones normalized to the steering direction of a dominant source and the standard deviation of phase angle, as shown in figure 5 and plotted in figure 4.

(d) To test for randomness in each data set

Results of the number-of-runs test for all beams and two hydrophones. Single listing for each analysis frequency in each time-period, as shown in the ZRUN column in figure 5.

(e) To test for transients and "outliers" in the data set

Results of the mean-square successive difference test for all beams and two hydrophones. Single listing for each analysis frequency in each time-period, as shown in the ZMSSD column of figure 5.

(f) To detect linear trends

Kendall's rank correlation coefficients for all beams and two hydrophones. Single listing for each analysis frequency in each time-period, as shown in the ZTAU column of figure 5.

(g) To test whether the towship noise is dominating the sidelobes

Spearman's rank correlation matrix. Single matrix for each analysis frequency in each time-period, as shown in figure 6.

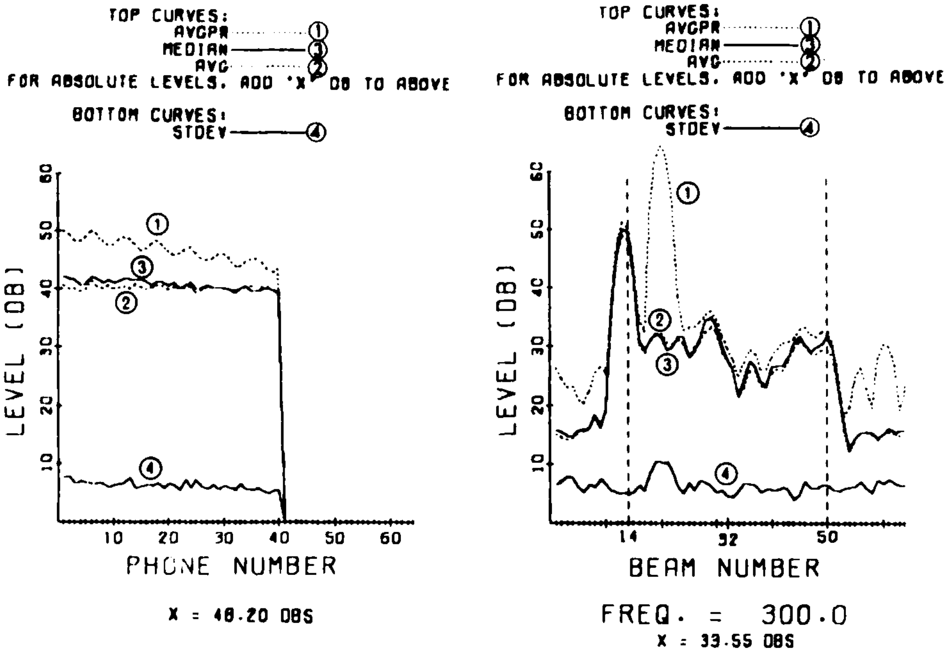
(h) To spot persistent anomalous patterns in the noise-level response

Polar plots of the 50 percentile (median) noise levels on all beams receiving acoustic energy. Done for each analysis frequency for each time-period of the directionality polygons, as shown in figure 7. The median level for each beam-noise time-period is also listed in the MEDIAN column of figure 5.

Additional discussion of how these statistics can be used to assess the performance of the measurement system and data quality are given in references 1, 2 and 3.

TABLE 1. PRODUCTS OF THE DATA-PROCESSING SYSTEM

Quality assessment	Analysis	Description	Figure
•		Plots of (1) average noise-power levels; (2) geometric mean intensity levels, (3) median levels, (4) standard deviations of the levels as a function of all hydrophones. Done for each analysis frequency in each time-period.	3(a)
•		Plots of (1) average noise-power levels; (2) geometric mean intensity levels; (3) median levels, (4) standard deviations of the levels as a function of all beams. Done for each analysis frequency in each time-period. Differences between (1) and (2) are sometimes plotted.	3(b)
•		Plots of (1) average and median phase and standard deviation of the phase as a function of hydrophone for a high level source.	[illegible]
	•	10, 25, 50 (median), 75 and 90 percentiles of noise levels at all beams and two hydrophones. Single listing for each analysis frequency in each time-period.	5 (10% to 90%)
•	•	Geometric mean intensity levels (decibel averages) on all beams and two hydrophones. Single listing for each analysis frequency in each time-period.	5 (AVG)
•	•	Average noise-power levels on all beams and two hydrophones. Single listing for each analysis frequency in each time-period.	5 (AVGPR)
•	•	Standard deviations of all beams and two hydrophones. Single listing for each analysis frequency in each time-period.	5 (STDEV)
•		Skew and kurtosis for all beams and two hydrophones. Single listing for each analysis frequency in each time-period.	5 (SKEW) [illegible]
•		Results of the number-of-runs test for all beams and two hydrophones. Single listing for each analysis frequency in each time-period.	5 (ZRUN)
•		Results of the mean-square successive difference test for all beams and two hydrophones. Single listing for each analysis frequency in each time-period.	5 (ZMSSD)
•		Kendall's rank correlation coefficients for all beams and two hydrophones. Single listing for each analysis frequency in each time-period.	5 (ZTAU)
•		Differences between the average noise-power level and the geometric mean intensity level on all beams and two hydrophones. Single listing for each analysis frequency in each time-period.	5 (PRDIF)
•		Spearman's rank correlation matrix. Single matrix for each analysis frequency in each time-period.	6
	•	Plots of the cumulative distribution functions of noise levels for selected beams or groups of beams. Done for each analysis frequency for each time-period and for the combined data set from each directionality polygon.	10
•	•	Polar plots of the 50 percentile (median) noise levels on all beams receiving acoustic energy. Done for each analysis frequency for each time-period of the directionality polygons.	7
	•	Plots of high resolution spatial spectra obtained from the beam-noise data by the WB² high resolution algorithm.	[illegible]
	•	Polar plots of the estimates of the horizontal directionality derived from the 50 percentile (median) noise levels by deconvolving the beam response and resolving the ambiguities. Done for each analysis frequency for the combined data set from each directionality polygon.	
	•	Polar plots of the estimates of horizontal directionality derived from the 10, 25, 50 (median) percentile noise levels for beams. Done for each analysis frequency for the combined data set from each directionality polygon.	12
	•	Omnidirectional noise levels. Single value for each analysis frequency, obtained from the combined data set from each directionality polygon.	9 (values)
	•	Plots of the azimuthal anisotropy cumulative distribution function (AACDF). Done for each analysis frequency for the statistics tows and for the combined data set from each directionality program.	13
	•	Polar plots of S/N gain improvement versus array heading for a specified detection sector, called array heading roses.	14



(1) average noise-power levels,

(2) geometric mean intensity levels,

(3) median levels,

(4) standard deviations of the levels. (Levels are in dB//μPa^2/Hz.) As functions of all hydrophones or o^c all beams for each analysis frequency.

(a) Phone level plots (b) Beam level plots

Figure 3. A data-processing output

3.2 Additional description of statistical tests

Several products and statistics for the assessment of the measurement system's performance and data quality are listed in Table 1, most of which require no further explanation. However, the following four tests are not as universally well known and will be described in more detail below:

- Numbers of runs test

- Mean-square successive difference test

- Kendall's rank correlation coefficient

- Spearman's rank correlation matrix.

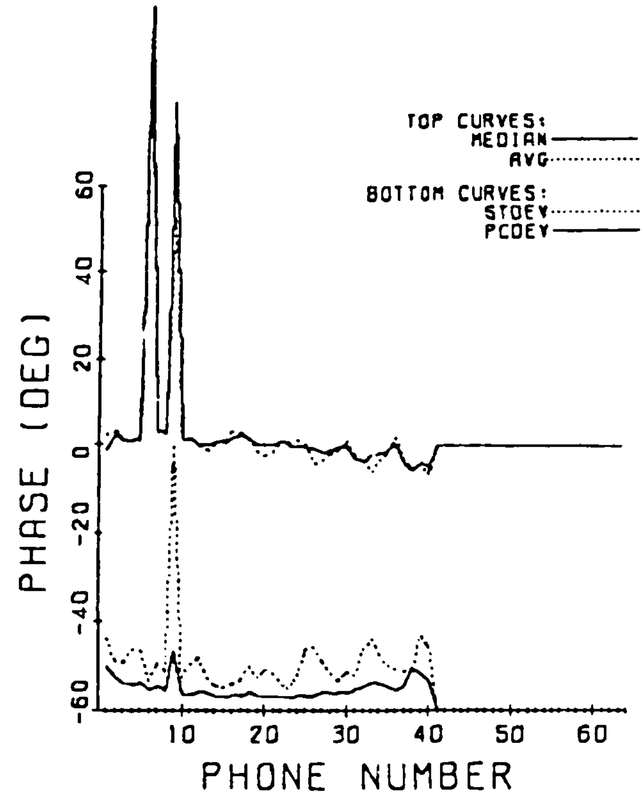


Figure 4. A data-processing output : median, average, standard deviation and percent of deviation in relative hydrophone phase angle across the array

3.2.1 Number-of-runs test

The number-of-runs in any time-period of beam-noise measurements is a non-parametric statistic (ie, a statistic that is independent of the actual distribution function for the data set under investigation). The number-of-runs is used as one measure of randomness in a series of observations. The attribute under consideration is randomness in the arrangement of beam-noise levels in a time-period and not in the distribution of beam-noise level magnitudes. Consequently, the number-of-runs statistic indicates the temporal randomness of the process that generated the noise levels observed at the beamformer output (ie, the randomness of the beam-noise data in the time domain).

KEY TO FIGURE 5

The heading lists the following

DATE	Date
TACTIC	Code for the exercise site
ST TIME	Start time of series
FREQUENCY	Analysis frequency
SOUND SPEED	In metres/second
LONG, LAT	Longitude, Latitude of beginning of series
SAMPLE SIZE	Number of data in time-series
LEG	Leg of directionality polygon
HEADING	Absolute heading of array
GAIN	Gain of signal-conditioning unit
SIDELOBE	Assumed sidelobe level of beams
DEPTHS	Depths of the array (m). Depth of bottom (m or fm)
WEIGHT	Sampling window
ARRAY	Low-frequency or high-frequency array
# AVG	Number of elements averaged = Time × bandwidth product (T×BW)

Lines 1 to 64 refer to beams. Lines 65 and 66 refer to hydrophones, line 65 being the time series of median level data selected from all hydrophones and line 66 being a single hydrophone selected for comparison. The columns refer to the statistics calculated over the sampled time series, as follows.

The columns list, from left to right:

BEAM	Beam or hydrophone number
RHDG	Heading (°) of ambiguous beam pairs relative to array orientation
THDG	True heading (°) of ambiguous beam pairs (right)
THDG	True heading (°) of ambiguous beam pairs (left)
BW	Beamwidth at 3 dB
10%	10 percentile noise level (dB)
25%	25 percentile noise level (dB)
MEDIAN	50 percentile (Median) noise level (dB)
75%	75 percentile noise level (dB)
90%	90 percentile noise level (dB)
AVG	Geometric mean intensity level (dB average)
AVGPR	Average noise-power level (dB)
STDEV	Standard deviation (dB)
SKEW	Skew (dB)
KURT	Kurtosis (dB)
dB	Number of beam data-samples used to calculate statistics
ZRUN	Number of runs test
ZMSSD	Mean-square successive difference test
ZTAU	Kendall's rank correlation coefficient
PRDIF	Power difference (AVGPR - AVG) (dB)

The text at foot reads as follows:

For beams □ to □ the mean value of the median levels is □ dB, the standard deviation is □ dB.
For beams □ to □ the mean STDEV is □ dB, the standard deviation of STDEV is □ dB.
For all beams the dynamic range of the median levels is □ dB.
The omnidirectional noise level estimated from the median levels of beams □ to □ is □ dB.
The number of virtual beams used is □ , the virtual beam power level is □ dB.

Beam □ is the median phone.
Beam □ is phone □
Processed on □□□

DATE 10/11/1981 SAMPLE SIZE 50
TACTIC 61 LEG 1
ST TIME =1018 0 HEADING = 270
FREQUENCY = 1000 0 GAIN = 30 0
SOUND SPEED =1499 SIDELOBE = 45 0
LONG= 10 33 N LAT= 43 57 W
DEPTHS = 131 139 2650 121 129 M
WEIGHT = HANN
ARRAY = HIGH
# AVG = 1

BEAM	RHDG	THDG	TMDG	BM	10%	25%	MEDIAN	75%	90%	AVG	AVGPR	STDEV	SKEW	KURT	DB	ZRUN	ZMSSD	ZTAU	PRDIF
1					30 3	35 7	41 6	45 9	50 4	41 0	46 0	7 81	- 74	1 31	50	- 286	- 999	712	5
2					30 2	41 2	46 0	49 7	52 6	44 6	49 7	8 03	- 74	40	49	- 719	584	1 041	5 1
3					37 6	45 2	48 8	52 9	56 6	48 2	52 7	7 78	-1 15	2 60	50	857	- 177	1 449	4 6
4					33 1	40 0	44 3	48 3	51 2	43 6	47 5	6 70	- 55	- 01	50	286	-1 065	394	3 9
5					34 1	38 8	43 0	47 6	50 9	42 6	46 6	6 95	- 77	1 44	50	286	-1 412	907	4 [illegible]
6					38 0	43 1	47 2	51 9	55 1	46 9	50 9	6 35	- 17	- 37	50	1 429	- 188	1 249	4 0
7					44 7	46 9	52 8	57 0	60 5	52 4	56 1	6 69	- 72	41	50	-1 715	-1 653	1 091	3 6
8					45 4	49 8	54 6	58 7	61 1	53 7	57 2	6 43	- 73	96	50	286	- 082	402	3 5
9					65 3	69 2	75 6	77 7	82 6	74 2	77 8	6 10	- 23	- 51	50	-2 000	-1 876	1 234	3 6
10					76 0	80 2	85 3	88 2	92 6	84 6	88 2	6 25	- 38	- 07	50	- 857	-1 512	1 173	3 6
11					79 9	83 8	88 9	92 1	96 5	88 4	92 0	6 33	- 67	13	50	- 857	-1 337	1 081	3 6
12	13 0	283 0	257 0	26 03	78 9	82 9	87 9	91 2	95 7	87 3	91 0	6 37	- 49	28	50	- 857	-1 172	905	3 7
13	23 7	293 7	246 3	15 86	72 8	76 9	81 4	85 0	89 6	81 2	84 8	6 31	- 42	05	50	- 857	- 946	721	3 7
14	30 1	300 1	239 9	12 74	57 0	60 6	65 1	69 7	73 4	65 5	69 0	5 80	03	- 74	50	857	360	151	3 5
15	35 3	305 3	234 7	11 06	51 5	56 0	60 8	65 0	68 0	60 0	63 4	6 18	- 39	- 46	50	286	514	965	3 4
16	39 9	309 9	230 1	9 98	43 6	51 1	56 1	59 5	61 1	54 3	57 4	7 58	-2 05	5 91	50	0 000	- 375	444	3 2
17	44 0	314 0	226 0	9 21	45 6	52 4	55 8	59 0	61 2	55 0	57 4	5 64	- 96	53	50	0 000	- 554	-1 611	2 5
18	47 9	317 9	222 1	8 63	50 1	53 9	57 6	60 2	62 2	56 7	58 7	4 67	- 64	- 05	50	0 000	-1 864	-2 548	1 9
19	51 5	321 5	218 5	8 10	50 3	54 6	56 8	59 2	61 2	56 6	58 4	4 19	- 29	- 42	50	-1 143	-1 754	- 873	1 8
20	54 9	324 9	215 1	7 82	51 1	54 1	57 3	60 6	62 5	57 1	59 2	4 53	- 15	- 64	50	572	1 305	- 888	2 1
21	58 2	328 2	211 8	7 53	50 5	55 5	57 8	60 3	63 5	57 5	59 6	4 65	- 41	05	48	-1 167	578	922	2 1
22	61 4	331 4	208 6	7 29	50 4	53 7	57 3	60 5	63 8	57 2	59 5	4 86	- 37	- 31	50	- 572	566	2 114	2 2
23	64 5	334 5	205 5	7 09	47 7	53 7	58 3	60 7	63 8	56 9	59 9	5 90	- 64	04	50	1 143	870	884	3 0
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25	70 4	340 4	199 6	6 79	54 9	56 5	61 6	64 4	66 0	61 2	63 8	4 82	08	- 33	50	1 143	955	118	2 6
26	73 3	343 3	196 7	6 68	53 1	58 6	61 8	64 4	68 1	61 2	65 1	6 19	- 34	39	50	-1 715	- 846	879	3 9
27	76 2	346 2	193 8	6 59	50 8	56 0	61 7	64 3	68 9	60 2	63 1	7 23	- 39	- 01	50	- 572	- 571	1 031	4 8
28	79 0	349 0	191 0	6 52	50 6	57 8	61 3	63 7	67 8	60 5	64 8	7 53	-1 12	2 19	50	0 000	058	1 425	4 3
29	81 7	351 7	188 3	6 47	54 1	58 2	63 5	68 4	70 6	63 1	66 5	6 55	- 68	06	50	1 143	925	771	3 5
30	84 5	354 5	185 5	6 43	58 3	63 0	67 9	70 8	73 5	66 7	69 3	5 46	- 53	- 64	50	1 143	430	1 166	2 6
31	87 3	357 3	182 7	6 41	59 9	62 3	68 1	71 7	73 8	67 0	70 1	5 97	- 55	- 22	48	875	088	1 108	3 1
32	90 0	0 0	180 0	6 40	54 7	61 8	65 6	68 2	72 0	64 7	67 9	6 21	- 64	- 06	50	572	466	1 208	3 3
33	92 7	2 7	177 3	6 41	54 1	59 1	61 8	65 7	67 5	61 7	64 3	5 18	- 51	19	50	572	209	2 274	2 5
34	95 5	5 5	174 5	6 43	48 6	57 1	61 3	64 4	66 8	60 1	62 8	6 02	- 86	- 05	50	-1 143	- 796	1 879	2 8
35	98 3	8 3	171 7	6 47	54 2	58 1	60 7	63 9	65 1	60 5	61 9	4 00	- 75	45	47	446	345	2 090	1 5
36	101 0	11 0	169 0	6 52	53 1	57 3	59 1	62 1	63 0	59 0	60 6	4 60	-1 49	3 22	50	- 286	367	632	1 6
37	103 8	13 8	166 2	6 59	47 1	54 8	57 5	60 9	62 9	57 1	59 6	5 40	- 82	54	50	572	012	1 210	2 [illegible]
38	106 7	16 7	163 3	6 68	49 4	55 0	57 5	60 5	62 2	56 9	59 3	5 54	-1 39	2 89	50	- 572	550	1 733	2 3
39	109 6	19 6	160 4	6 79	49 3	54 8	58 2	60 6	62 3	57 1	59 4	6 29	-2 25	7 02	48	875	- 403	- 462	2 1
40	112 5	22 5	157 5	6 93	53 1	55 5	59 1	61 4	63 5	58 3	60 0	4 64	-1 11	1 79	49	- 430	426	- 437	1 8
41	115 5	25 5	154 5	7 09	50 1	54 1	59 1	62 2	63 3	57 7	60 2	5 72	-1 02	1 01	50	857	167	101	2 5
42	118 6	28 6	151 4	7 29	48 8	54 7	58 9	61 6	63 2	57 9	60 3	5 33	- 79	52	48	-1 459	- 216	1 031	2 4
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46	132 1	42 1	137 9	8 63	44 6	52 2	56 4	59 6	61 1	55 0	57 8	6 26	-1 08	65	50	- 857	-1 399	- 511	2 8
47	136 0	46 0	134 0	9 21	47 3	52 4	55 5	57 9	59 2	54 4	56 6	5 27	-1 05	94	48	- 584	-1 430	545	2 2
48	140 1	50 1	129 9	9 98	46 5	50 4	54 5	57 4	59 8	53 8	56 1	5 13	- 54	- 52	50	- 572	- 396	1 149	2 3
49	144 7	54 7	125 3	11 06	46 9	52 2	56 1	57 9	59 4	54 5	56 8	5 43	-1 22	1 55	50	572	1 449	864	2 2
50	149 9	59 9	120 1	12 74	50 3	53 2	55 9	58 8	60 7	55 8	57 7	4 42	- 40	- 41	50	857	- 233	420	1 9
51	156 3	66 3	113 7	15 86	49 4	52 1	56 5	58 6	60 9	55 0	57 4	5 52	-1 05	1 15	50	572	-1 247	344	2 4
52	167 0	77 0	103 0	26 03	40 2	49 8	53 9	56 8	59 6	52 1	55 5	7 60	-1 63	3 01	50	572	- 421	570	3 4
53					42 1	45 6	50 4	53 7	56 1	49 7	52 5	5 30	- 20	- 70	48	875	- 228	612	2 8
54					32 3	40 3	44 8	47 7	50 0	44 0	47 4	6 34	- 72	49	50	572	- 878	419	3 5
55					28 3	36 8	40 0	43 6	47 5	39 3	43 1	7 39	-1 18	1 34	48	- 875	- 066	-1 638	3 8
56					38 8	40 9	44 6	48 8	50 0	44 5	47 2	5 19	- 25	- 07	50	572	- 548	361	2 7
57					41 2	45 5	47 9	51 6	55 0	48 1	51 2	5 63	- 45	76	50	-1 143	-2 083	880	3 1
58					40 3	44 5	48 2	52 9	55 3	47 9	51 1	5 95	- 52	24	48	- 584	-2 489	419	3 2
59					36 5	40 0	45 3	48 8	51 8	44 4	47 8	6 43	- 70	29	50	- 286	-3 030	017	3 4
60					34 8	37 2	41 2	44 7	49 4	40 8	44 1	6 10	- 72	3 10	50	-1 143	-2 552	- 050	3 3
61					37 5	41 0	44 4	48 4	53 0	44 9	47 9	5 42	06	- 94	50	- 857	-1 551	1 141	3 1
62					40 1	44 6	47 5	51 9	56 4	47 6	51 5	7 12	-1 23	3 14	50	- 857	- 788	915	3 9
63					35 9	42 9	46 2	50 3	55 8	46 0	50 3	7 03	- 53	11	50	- 286	-1 011	411	4 3
64					32 2	37 4	43 2	46 9	52 1	42 6	47 2	6 96	- 10	- 90	50	286	-1 072	- 050	4 6
65	0 0	0 0	0 0	0 00	80 0	83 9	88 9	92 1	96 3	88 4	91 8	6 05	- 36	- 16	50	- 857	-1 224	1 090	3 5
66	0 0	0 0	0 0	0 00	80 8	84 9	88 7	92 6	96 2	87 9	91 9	7 97	-1 65	3 92	50	-1 429	-1 026	1 148	4 1

FOR BEAMS #32 TO #50 THE MEAN VALUE OF THE MEDIAN LEVELS IS 58 49 DB THE STANDARD DEVIATION IS 2 57 DB
FOR BEAMS #32 TO #50 THE MEAN STDEV IS 5 55 DB THE STANDARD DEVIATION OF STDEV IS 83 DB
FOR ALL BEAMS THE DYNAMIC RANGE OF THE MEDIAN LEVELS IS 48 95 DB
THE OMNIDIRECTIONAL NOISE LEVEL ESTIMATED FROM THE MEDIAN LEVELS OF BEAMS #32 TO #50 IS 72 4 DB
THE NUMBER OF VIRTUAL BEAMS USED IS 19 THE VIRTUAL BEAM POWER LEVEL IS 47 47 DB

BEAM 65 IS THE MEDIAN PHONE
BEAM 66 IS PHONE 21

PROCESSED ON 10/11/1981 1110 11

Figure 5. A data-processing output: tabulated ambient noise statistics for a single time-period

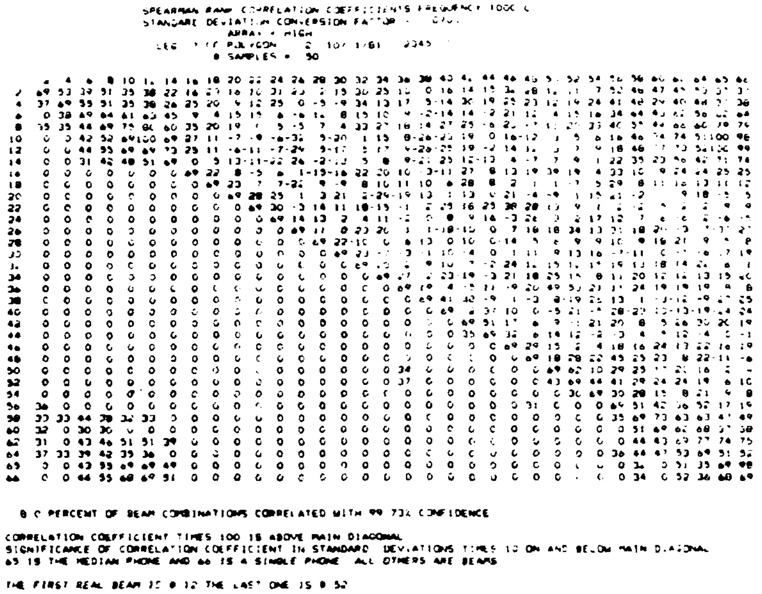
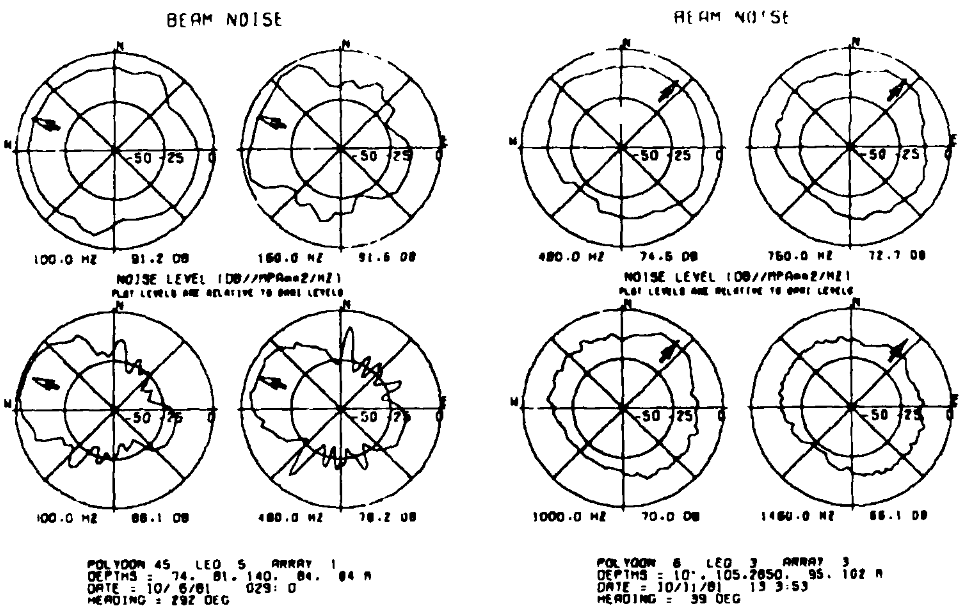


Figure 6. A data-processing output: Spearman's rank correlation matrix



(a) In low-sea state, spikes due to shipping

(b) In high sea-state in presence of shipping, no spikes showing

Figure 7. A data-processing output: polar beam level plots

In order to actually calculate the number-of-runs statistic(ref.4), beam-noise levels in the time-series must be transformed into three categories, according to whether they are:

- above the median beam-noise level (A's)
- below the median beam-noise level (B's)
- equal to the median beam-noise level (M's).

Individual beam-noise levels in the time-series are then replaced by the symbols A, B or M. Subsequently, samples equal to the median value (M's) are eliminated from the data set. Any unbroken sequence of like kinds (eg AA, BBB, etc.) in the revised time-series is counted as one run. The number-of-runs in the time-series, regardless of the length of the run, is then counted. The algorithm relates the number-of-runs actually counted (RUN) to the distribution of runs expected for any randomly distributed time-series containing (N_A) A elements and (N_B) B elements. Assuming that all the elements of the time-series have the same probability of occupying any position in the temporal sequence, a probability distribution for each realizable permutation of the A's and B's can be determined. Mathematically, the expected distribution of the number-of-runs in a large sample drawn from a randomly-distributed population can be approximated by a normal distribution of the variable R, with the mean and standard deviation values given by:

$$R = \frac{2N_A N_B}{N_A + N_B} + 1$$

$$\sigma^2_R = \frac{2N_A N_B(2N_A N_B - N_A - N_B)}{(N_A + N_B)^2 (N_A + N_B - 1)} .$$

The algorithm employed in the software calculates the quantity ZRUN (see figure 5, column 17), which expresses the number-of-runs actually counted (RUN) in terms of the statistics for the corresponding normal distribution:

$$ZRUN = \frac{RUN - R}{\sigma_R} .$$

That is, ZRUN is the deviation of the actual number-of-runs from the expected mean, normalized in terms of the expected standard deviation. Beam-noise time-series with too few or too many runs (ie, those with large values of the parameter ZRUN) are suspected to be products of non-random processes. It should be noted that a completely deterministic signal - such as an acoustic tone - could produce too few or too many runs, depending on its frequency, since the sampling interval is generally constant.

The ZRUN term can be used directly to eliminate beam-noise data sets that appear to have too few or too many runs. For example, one could arbitrarily state that any time-series with ZRUN > 2 should be eliminated from further consideration. However, since the expected distribution of the number-of-runs is normal, approximately 4.5% of the valid data would be rejected by such a criterion. An alternate and perhaps more appropriate screening method would eliminate data sets based on the confidence level associated with the hypothesis that the measured number-of-runs (RUN) is, in fact, a member of the normal distribution (R, σ_R^2).

3.2.2 Mean-Square Successive Difference Test

The Mean-Square Successive Difference (MSSD) Test attempts to verify that each measurement of beam-noise level in any particular time-series is independent of the next (successive) measurement in that time-series. Unlike the Number-of-Runs Test, the MSSD Test (figure 5, Column 18) uses the numerical value of each measured noise level as well as its relationship to the adjacent (successive) measurement in the time-series. This test is useful in identifying contamination of time-series data due to transients of both acoustic and non-acoustic origin.

The Mean-Square Successive Difference Test is based on the assumption that the measurements in any time-series are drawn from a normally distributed population with unknown mean and variance. Under this assumption, two methods can be used to estimate the population's variance, σ^2. One is the unbiased estimator:

$$s^2 = \frac{1}{N-1} \sum_{i=1}^{i=N} (x_i - x)^2$$

The other is:

$$\frac{d^2}{2} = \frac{1}{2(N-1)} \sum_{i=1}^{i=N-1} (x_{i+1} - x_i)^2,$$

one-half of the mean of the successive differences squared. If the time-series data are dependent or are not drawn from a normally distributed population, the two calculations should produce different estimates of the variance. For example, if the beam-noise time-series measurements are accumulated during periods containing steadily increasing or decreasing noise levels (ie, an upward or downward sloping ramp), the differences between consecutive samples would be smaller than those obtained for a completely random noise-field. Hence the $d^2/2$ estimate of the variance would be smaller than that calculated using the unbiased estimator.

When the beam-noise measurements contain strong, constant signals, the two estimates may or may not be significantly different. If the strong signal persists throughout the entire measurement interval, the two estimates would be nearly identical, since all the x_i levels are nearly uniform. However, if the strong signal is present only during a significant fraction of the measurement interval, the results produced by the two variance estimators will be substantially different. For these reasons, the MSSD Test may be viewed as a detection device for certain kinds of transient signals in the time-series data.

The algorithm employed calculates the test statistic ZMSSD, where:

$$\text{ZMSSD} = \frac{d^2/2s^2 - 1}{[(N-2)/(N^2-1)]^{\frac{1}{2}}}$$

If the assumptions concerning the beam-noise measurements are valid, the expected distribution of the test statistic ZMSSD can be approximated by a normal distribution with a mean value of zero and a unit variance.

The exact distribution of this test statistic has been tabulated for uncorrelated observations with sizes ranging from 4 to 60 samples (ref.2). For sample sizes greater than six, the normal distribution is a very good approximation at the 0.05 and the 0.95 significance levels. However, the normal distribution is not a good approximation of the exact distribution at the 0.001, 0.01, 0.99, and 0.999 significance levels until the sample size is greater than 60. Nonetheless, the normal distribution is a useful approximation, since it always yields conservative estimates. To indicate the magnitude of the differences, critical values of ZMSSD were calculated at various confidence levels using the normal approximation. Table 2 compares the results with the exact values (from reference 5) for a sample size of 60:

TABLE 2. COMPARISON OF ZMSSD RESULTS WITH EXACT VALUES

	Significance levels					
Critical values based on	0.001	0.01	0.05	0.95	0.99	0.999
Approximate normal distribution	-3.091	-2.327	-1.645	1.645	2.327	3.091
Exact distribution	-3.013	-2.306	-1.649	1.649	2.306	3.014

Since the accuracy of the normal distribution approximation improves as the sample size increases, the approximation should be more than adequate for beam-noise sample sizes of 60 or more.

MSSD Test results (ie, the quantity ZMSSD) are interpreted and used in much the same manner as the Number-of-Runs Test results (ZRUN). The quantity ZMSSD can be used directly to eliminate data sets from further processing actions or it may be used to test the hypothesis that the beam-level measurements contained in any time-series are distributed in a random manner (ie, are not correlated). In the latter case, tabulated critical values for the appropriate normal distribution are required to confirm (or reject) the statistical hypothesis.

3.2.3 Kendall's rank correlation coefficient

The Kendall rank correlation coefficient is a non-parametric (distribution free) statistic that provides a measure of the correlation between two se : of ranked observations(ref.6). Kendalls' rank correlation coef::cient is used to measure the correlation between each time-series of beam-noise measurements and a set of monotonically increasing integers (1, 2, 3,...,N). The monotonically increasing data set used for each correlation assessment is identical to the ranked order of any continuously increasing function. Therefore, increasing trends in any time-series of beam-noise measurements result in positive values of the correlation coefficient, while decreasing trends produce negative values. The absolute magnitude of the correlation coefficient provides an indication of the duration of the trending portion of the time-series relative to the length of the sample under consideration. Although the concept is similar in some respects to the number-of-runs statistic, the Kendall rank correlation coefficient uses much more of the information present in the time-series and is considerably more powerful (in a mathematical sense) than the ZRUN and ZMSSD results described previously when testing for a linear trend.

In order to calculate Kendall's rank correlation coefficient, each observation in the time-series must be replaced by its ranking relative to all other measurements in that particular time-series. As used here, the term 'rank' implies that all measurements in the time-series can be rearranged in a monotonically increasing sequence from the minimum to the maximum value (ie, ordered according to the magnitude of the measurements). Each measurement value is then assigned a numerical rank and, in turn, the numerical ranks are substituted into the original time-series in place of the measured values. Multiple occurrence of certain values in the original time-series (ie, tied data points) complicates the process, since it requires somewhat more bookkeeping, but the end result is essentially the same. Ties are treated in the usual manner and are assigned the same fractional rank. For example, if there is an n-way tie for the rank r_i, the numerical rank assigned to each of these values is:

$$\frac{r_i + r_{i+1} + r_{i+2} + \ldots + r_{i+n-1}}{n} .$$

Consequently, the next rank available for use in the sequence is r_{i+n}. In either case, the resultant sequence of numbers presents the numerical rank of each value in the original time-series relative to all others in that series.

Numerical data for the calculation process are obtained by examining the relationship between each pair of ranks in the modified time-series (r_a, r_b, r_c, r_d, ..., r_u), beginning with the element r_a. The u-1 pairs containing $r_a[(r_a, r_b), (r_a, r_c), \ldots, (r_a, r_u)]$ are examined first, then the u-2 pairs containing r_b [eg, $(r_b, r_d), \ldots, (r_b, r_u)$] are considered, and so on until the end of the sequence is reached. A score of +1 is assigned to each pair having the ranks in ascending order (eg, the pair 2, 6) while a score of -1 is assigned to each pair having the ranks in inverse order (eg the pair 7, 5). Scores for each individual pair are summed to obtain the total score (S) for the modified time-series. If there are no tied data points, the Kendall rank correlation coefficient, τ, is defined by the following:

$$\tau = \frac{\text{total score}}{\text{maximum possible score}} = \frac{S}{\frac{1}{2}N(N-1)} ,$$

where N = the number of measurements in the time-series.

When there are tied data points, the Kendall rank correlation coefficient is defined by:

$$\tau = \frac{S}{[\frac{1}{2}N(N-1)]^{\frac{1}{2}}\,[\frac{1}{2}N(N-1) - T]^{\frac{1}{2}}} ,$$

where $T = \frac{1}{2}\,\Sigma t_j\,(t_j - 1)$,

and t_j = the number of elements in the jth group of tied data points.

The Kendall rank correlation coefficient can have any value from +1 to -1. If the series of ranks is a monotonially ascending sequence from 1 to N, it is obvious that τ will be equal to 1. Similarly, if the series of ranks is a monotonically descending sequence from N to 1, it is clear that τ will be equal to -1. The value of τ observed in any time-series may be used directly as a criterion to eliminate highly correlated data sets. For example, any time-series could be considered unsuitable for deconvolution processing if $\tau > \tau_{max}$.

As stated at the outset, the Kendall rank correlation coefficient is used to detect trends in time-series data. Consequently, the expected distribution of τ must be determined for samples drawn from a randomly-distributed population. Assuming that each element of the time-series has an equal probability of occupying any position in the temporal sequence, then the expected probability distribution of the parameter τ can be developed for every sample size N. Indeed, such tables are available - even for moderately large sample sizes (ie, $N < 40$). For larger samples from a randomly-distributed population, the parameter τ can be considered as a normally distributed variate with a mean value of zero and a variance of:

$$\sigma_\tau^2 = \frac{2(2N + 5)}{9N(N-1)} .$$

The algorithm employed in the onboard acoustic data-processing software calculates the quantity ZTAU (figure 5, column 19) which expresses the Kendall rank correlation coefficient actually observed (τ) in terms of the parameters for the expected distribution:

$$ZTAU = \frac{\tau}{\sigma_\tau} .$$

The statistic ZTAU is interpreted and used in much the same manner as the terms ZRUN and ZMSSD described previously. Each is a normally distributed variate with a mean value of zero and a unit variance. They are used in conjunction with tabulated values for the normal distribution to confirm or reject statistical hypothesis relating the time-series under consideration with a known (normal) probability distribution.

3.2.4 Power difference

One of the simplest and most powerful tests for transients in the beam-noise data is the difference between the average power level and the geometric mean intensity level (PRDIF). This can be expressed as

$$\text{PRDIF} = 10 \log\left[\frac{1}{n}\sum_{i=1}^{n} 10^{(R_i/10)}\right] - \frac{1}{n}\sum_{i=1}^{n} R_i$$

where R_i is the ith beam noise level in this beam-noise time series. Experience indicates that under normal conditions PRDIF is approximately 2 to 2.5. Greater values than this will occur when high level transients are present in the data. This results from the characteristic of the average power level to be dominated by the high level components while the geometric mean intensity level (dB average) treats the data as an arithmetic sequence in decibels and is relatively insensitive to a few high level data points.

3.2.5. Spearman's rank correlation matrix

The degree of association between two series of measurements can be estimated by calculating the Spearman's rank correlation coefficient, r_s(ref.7). This statistic can be used to measure the correlation between noise-measurement sequences obtained simultaneously on any two beams. Consequently, if any two series of beam-noise measurements are highly correlated, there is a corresponding probability that a common noise-source is the cause of both sets of measurements. An example is when the noise from the towship dominates the low-noise-level beams: comparing the low-noise-level beam with one receiving the noise of the towship gives a high Spearman's rank correlation coefficient which is evidence that the two are correlated and a potential problem exists.

Spearman's method of analysis is similar to that used in calculating Kendall's rank correlation coefficient because it deals with the ranks of the observations and not with the magnitudes of the measurements themselves. It is also a distribution-free (non-parametric) statistic and does not depend on any assumptions concerning the probability distribution of the values in either time-series.

To calculate Spearman's rank correlation coefficient, the observations in each set of beam-noise measurements must be replaced with their ranking relative to all other observations in that set (ie, the measurements from beam 'j' are ranked separately from those of beam 'k'). The procedure used to rank each set of observations is identical to that described previously for Kendall's rank correlation coefficient and will not be repeated here. The ranks of corresponding positions in the two temporal sequences are then compared pair by pair (ie, the rank of the first measurement in the time-series for beam 'j' is compared with the rank of the first measurement in the time-series for beam 'k'; this process is repeated for each of the N positions in the temporal sequences). Spearman's rank correlation coefficient is calculated by the following:

$$r_s = 1 - \frac{6}{N(N^2-1)} \sum_{j=1}^{j=N} d_j^2$$

where d_j = the difference between the ranks of corresponding elements in the two temporal sequences.

Spearman's rank correlation coefficient (r_s) can have any value from +1 to -1. If the two series are identical, it is obvious that d_j will always be zero and that r_s will equal +1. Similarly, if one time-series is a mirror image of the other, it can be shown that r_s will always be equal to -1. Spearman's rank correlation coefficient can be used directly to identify data sets that appear to be strongly correlated. For example, data from two beams that are widely separated in space would be suspected of contamination if $r_s > r_{s\ max}$ (determined by level of confidence desired).

The coefficient may also be used as a test for significance, since the expected distribution of r_s is known to be symmetrical around the value 0, to approach the normal curve as N becomes large, and to be truncated at -1 and +1. Typically, the test for significance is applied to test the null hypothesis that the rank correlation coefficient in the population is zero, or we may say that the observations in the population are independent. Tables for r_s are available for small sample sizes ($N < 20$)(ref.8,9). For large sample sizes the sampling distribution is close enough to normality that the normal area table may be used to find the probabilities. In this case the variance of r_s is given by:

$$\sigma_r^2 = \frac{1}{N-1}\ .$$

As in previous tests, the observed coefficient (r_s) may be expressed in terms of the expected distribution ($0, \sigma_r^2$) by the following:

$$ZSP = \frac{r_s}{\sigma_r}.$$

In conjunction with tabulated values for the normal distribution, the test statistic ZSP may be used to confirm or reject the independence hypothesis at any desired level of significance.

The correlation coefficients and their corresponding levels of significance (ZSP) are displayed in a rectangular matrix. Figure 6 is an example. The top row and left-hand column are beam numbers (the last two elements in each are for hydrophones). The elements above the main diagonal are the correlation coefficients (x100, for display purposes) and those on and below are the confidence levels in standard deviations (x10, also for display purposes). To facilitate picking out possible problem areas, all significance levels less than three standard deviations (3σ in the matrix) have been replaced by zeroes. The remaining elements indicate that the hypothesis of independence can be rejected with a confidence level of greater than or equal to 99.73%.

The most important part of the matrix is what is printed below the main diagonal. A non zero element indicates correlation in a pair of beams as a beam and hydrophone. A zero below the main diagonal is indicative of non correlation, at least at the 99.73% level. Furthermore, a non zero number (ie 35) below the main diagonal darkens more area than a single zero. Hence, the rank correlation matrix can be used as grey scale indicator of correlation. The darker the matrix is below the main diagonal the more wide spread the correlation and potential array degradation. This test used in conjunction with the beam noise level plot and multiple beam levels (figure 3) is an excellent indicator of sidelobe suppression level as beam noise contamination level (see Section 3.2.6 on virtual beams).

3.2.6 Virtual beams

At frequencies below design frequency, virtual beams will be produced automatically by the FFT beamformer. These are the beams that are formed by time delaying (in a time-domain beamformer) or phase shifting (in a frequency-domain beamformer - FFT beamformer for example) the signals from the array of hydrophones more than is necessary to form an endfire beam. These are the beams in figure 3(b) that have beam numbers less than 14 or greater than 50.

Since the virtual beams do not have main lobes in real acoustic space, they are usually ignored. However, they contain energy from various incoherent sources of self-noise and coherent acoustic energy through sidelobes in the acoustic domain. Simple statistics calculated from the outputs of these virtual beams can be used to help determine the levels and sources of self noise, the operating condition of the system, and the levels of sidelobe suppression. These statistics can also be used as a signal for the existence of problems and as a guide for locating the problems.

There are at least three ways in which the virtual beams receive energy.

(1) Virtual beams, like real beams, have sidelobes that extend into real space. If the sidelobe rejection of the beamformer is poor, strong sources from acoustic space can "leak" acoustic energy into the virtual beams.

(2) There could be energy propagation in the array at a speed lower than the speed of sound in the sea. This energy would appear on one virtual beam.

(3) There is energy on the hydrophones that is not coherent from one hydrophone to another. This energy may be of non-acoustic (flow noise), electronic, or mechanical (shocks, vibrations) origin. These incoherent noises are spread among all the beams, real and virtual. However, they are most easily spotted in the virtual domain because there is normally less energy there to mask them.

The energy in the virtual beams can therefore be invaluable for quality checking and "grooming" the towed-array system.

Additional discussion of virtual beams is available in reference 3.

4. BEAM NOISE ANALYSIS PRODUCTS

Once the quality of the measurements has been evaluated as described in Section 3, the appropriate data-processing products of Table 1 are used to analyse the ambient noise. This is done under six headings:

(1) Omnidirectional noise levels

(2) Horizontal directionality

(3) High resolution spatial spectrum

(4) Temporal statistics

(5) Spatial statistics

(6) Array heading roses

The purposes and procedures for these analyses are described below in Sections 4.1 through 4.5 respectively.

4.1 Omnidirectional noise levels

Measuring the omnidirectional level of underwater ambient-noise is not a simple, straight-forward task when the measurement tool is a towed array. This is because the towship is always present and the array is being towed at speeds of up to five knots when measurements are taken. The proximity of the towship contributes significantly to the measured noise. The noise received from the towship can be as much as 69 dB at 1.5 kHz and 89 dB at 300 Hz if the distance between the towship and the array is 1000 m (which is typical). The ambient-noise, on the other hand, can be more than 10 dB below these levels.

The technique used to estimate the omnidirectional level of the ambient-noise is the same as that used to estimate its horizontal directionality, which is described in Section 4.2 below. In fact the omnidirectional level is obtained by integrating (or summing) the levels of noise over all azimuths in the directionality pattern. The towship noise has very little influence on the directionality pattern, since the beams dominated by towship noise are eliminated in the noise-directionality calculations. Hence the omnidirectional level is an average value for the period over which the measurements are taken.

The output, which consists of a single value for each analysis frequency, is printed as part of the output of the horizontal directionality measurement, as shown in figure 8.

4.2 Horizontal directionality

4.2.1 Purpose

The major objective of the measurements made during the directionality polygon manoeuvres is to provide appropriate data to resolve ambiguities and to estimate the directionality of persistent background noise. The concept of a "persistent background-noise directionality" is applicable only when all the factors that influence the ambient noise are reasonably stable over long periods (6 hours to 6 months) and when the factors are generally repeatable so as to yield approximately the same directionality pattern. Seasonal patterns in either acoustic-propagation or in shipping lanes create conditions that satisfy both these requirements: their contributions to the ambient-noise level remain reasonably stable during a given season and repeat themselves for the same season in successive years. If such conditions exist, the final criterion is the relationship of these factors to the noise level at a given site. For example, for a site at the intersection of several shipping lanes, the nearby ships may appear randomly distributed in range and azimuth and the concept of a persistent background-noise directionality may not be applicable. At a site one hundred miles removed, however, the shipping patterns may appear well defined and support the concept of persistent background-noise directionality.

Because the same general directionality pattern can be expected to occur whenever future conditions are about the same, the concept of a persistent background noise is the key to limiting the number of measurements required to characterize the ambient noise in a given area. This also reduces the time needed to acquire a data base for the validation of ambient-noise models.

4.2.2 Method

Horizontal directionality is estimated by the Wagstaff's Iterative Technique (WIT) algorithm(ref.10). This is a constrained iterative restoration algorithm that restores some of the high-order spatial harmonics filtered out by the low-pass spatial response of the array. Its present version contains corrections for array tilt, three-dimensional beam-response patterns, and noise-field vertical arrival structure(ref.11). The technique is basically as follows. WIT uses the median beam-noise values from all legs of a directionality polygon to "guess" the horizontal directionality. The beam patterns of the array on the various headings of the polygon are then convolved with this guess to calculate median beam-noise levels. These calculated levels are compared with the corresponding measured levels and the "guess" is appropriately modified along azimuths of disagreement. This convolution, comparison, and modification procedure is repeated until the agreement is within predetermined limits. Such an iterative procedure actually deconvolves the array beam patterns from the data. In some cases, where the noise-field is reasonably stationary, the measured and calculated beam responses are so close that it could be said that the array cannot tell the difference between the estimated and the actual noise-fields. When data from only one heading (leg) are used the result is a deconvolution of the data.

The noise levels of the beam contaminated by the towship can be up to 20 dB greater than beams considered free of contamination. Even so, the ability of WIT to discriminate against or eliminate this contamination is sufficient to produce good-quality estimates of the noise-field directionality.

The output of WIT is a polar plot of the estimates of the horizontal directionality derived from the 50 percentile (median) noise levels (figure 8). This is done for each analysis frequency of the data set and obtained by combining the median beam-noise levels of each leg of the directionality polygons. The result is usually plotted in a polar format such as figure 8 and is often referred to as a "noise rose". In addition, as explained under Section 3.1(h), polar plots of the 50 percentile (median) noise levels on all beams receiving acoustic energy (figure 7) are generated for the time-series of each leg so that anomalous response patterns can be easily spotted.

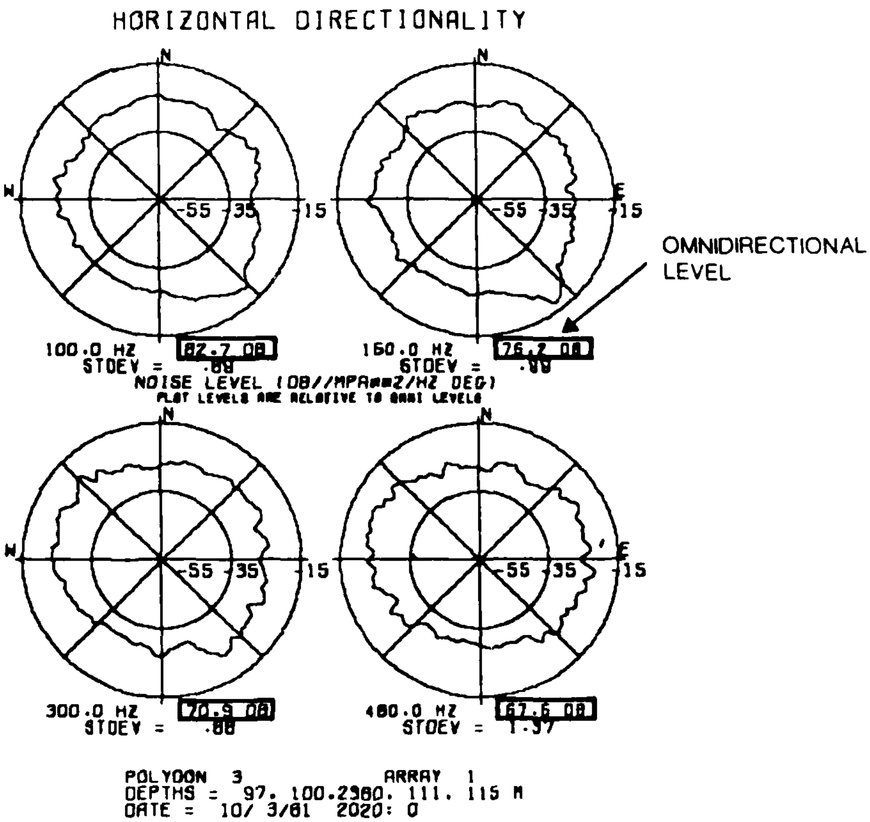


Figure 8. A data-processing output : horizontal directionality plots and omnidirectional noise levels

4.3 High resolution spatial spectra

4.3.1 Purpose

The beam-noise versus beam numbers data can be processed by the Wagstaff-Berrou Broadband (WB^2) algorithm(ref.12) to obtain high resolution ambiguous spatial spectra. This technique estimates levels and relative azimuths much better than can be done from the original beam-noise data. This is illustrated by a typical example in figure 9.

4.3.2 Method

The WB^2 technique is a high-resolution algorithm for estimating the noise-field which produced the beam-noise data. WB^2 operates on the spectrum analysed beam-noise data for one time period rather than the hydrophone data. The technique starts with an initial guess of the spatial spectrum and convolves it with the beam patterns in cosine space. The differences between the estimated beam-noise levels and the corresponding measured beam-noise levels are used to appropriately modify the guessed spectrum within the coverage areas of those beams showing the disagreement. The resulting new spectral estimate is convolved with the beam patterns again and compared with the measured beam-noise levels. This process of modification of the spectral estimate, convolution, and comparison with the measured beam-noise data is repeated until the agreement is within predetermined limits or a fixed number of iterations is reached, which ever comes first.

The WB^2 algorithm can be considered an optimized version of WIT which takes advantage of simplifications in testing and spectral estimate modification. These simplifications are made possible by performing the estimation procedure in cosine space where the beams are all the same size and shape and by estimating the ambiguous noise-field spatial spectrum for only one array heading and one time period. Like WIT, a key to the success of WB^2 is that the estimation process is performed in the log transformed space (decibels) rather than in beam power space.

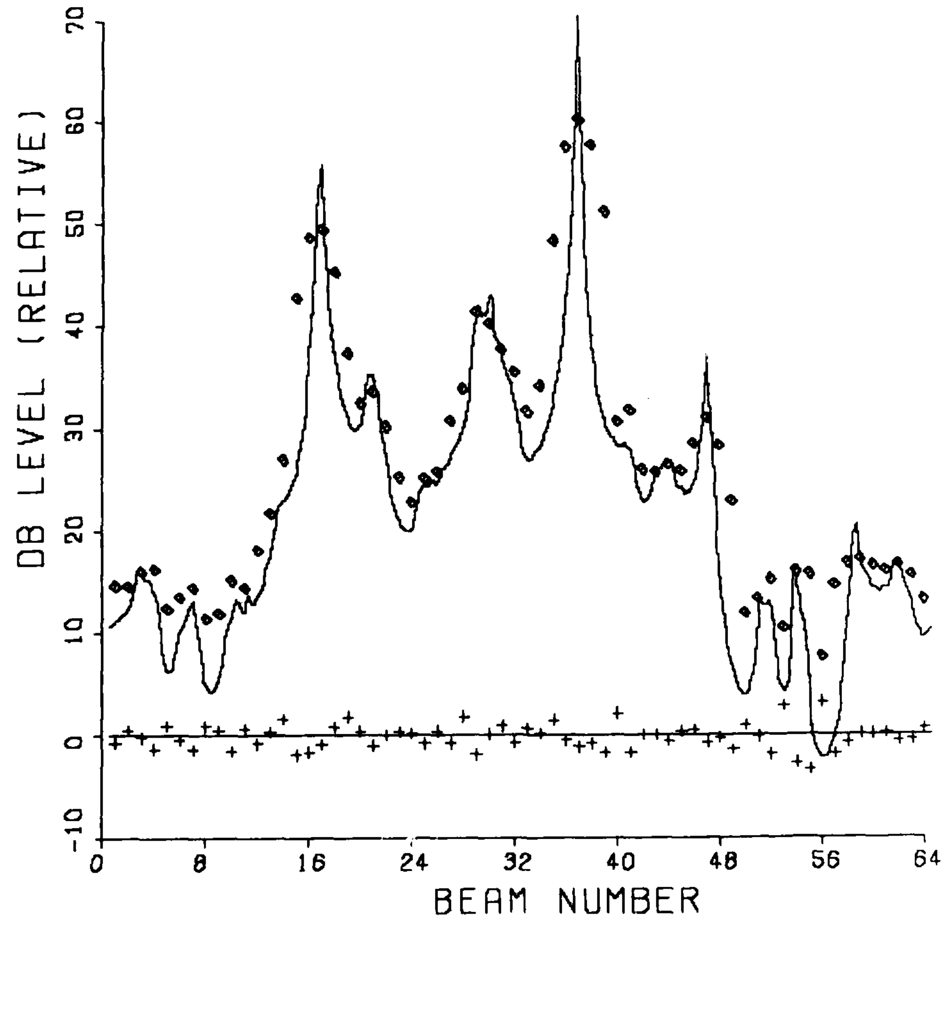


Figure 9. WB^2 results for high resolution spatial spectra

4.4 Temporal statistics

4.4.1 General

The minimum number of samples that gives statistical significance for one time-series is considered to be about 50. During the directionality polygon manoeuvres data are acquired during 15 min time periods (about one sample every 15 s) on each heading. Thirty minutes are usually required for turning and stabilizing the array after each leg of the polygon. Thus it is just possible to acquire a complete set of beam-noise time-series data for each polygon leg in about 45 min.

However, by collecting data over much longer periods it is possible to power-average the time-series over up to ten consecutive samples to generate new time-series of down to one-tenth of the original size, thereby giving time-bandwidth products (TxBWs) of up to 10. This extends the applicability of the results to those sonar systems operating on a time-bandwidth products TxBW of greater than one.

Thus, although the data collected during the directionality polygon manoeuvres are also used to analyse the temporal statistics, that is not considered to be their primary purpose. Instead, separate "statistics tows" are conducted especially for that purpose. These tows last for up to 12 h on a constant heading, allowing the number of samples in their data sets to reach the present processing limitation of 250. This allows the creation of analysis products with TxBWs of up to 10.

The analysis products generated to characterize the temporal statistics of the ambient noise are:

(a) 10, 25, 50 (median), 75 and 90 percentiles of noise levels at all beams and two hydrophones. Single listing for each analysis frequency in each time-period, as shown in the 10% to 90% columns of figure 5.

(b) Geometric mean intensity levels (decibel average) on all beams and two hydrophones. Single listing for each analysis frequency in each time-period, as shown in the AVG column in figure 5.

(c) Average noise-power levels on all beams and two hydrophones. Single listing for each analysis frequency in each time-period, as shown in the AVGPR column in figure 5.

(d) Standard deviations of all beams and two hydrophones. Single listing for each analysis frequency in each time-period, as shown in the STDEV column in figure 5.

(e) Skew and kurtosis for all beams and two hydrophones. Single listing for each analysis frequency in each time-period, as shown in the SKEW and KURT columns in figure 5.

(f) Plots of the cumulative distribution functions of noise levels for selected beams or groups of beams. Done for each analysis frequency for each time-period and for the combined data set from each directionality polygon, as shown in figure (10) in Section 4.4.2.

(g) Polar plots of the estimates of noise horizontal directionality derived from the 10, 25, 50 (median) percentile noise levels for beams. Done for each analysis frequency for the combined data set from each directionality polygon, as shown in figure 12 in Section 4.4.3.

The uses and methods of calculating products (a) to (e), which are listings of values for each analysis frequency in each time-series, are self-explanatory. Products (f) and (g) are plotted products however, and are described separately in Sections 4.4.2 and 4.4.3 below.

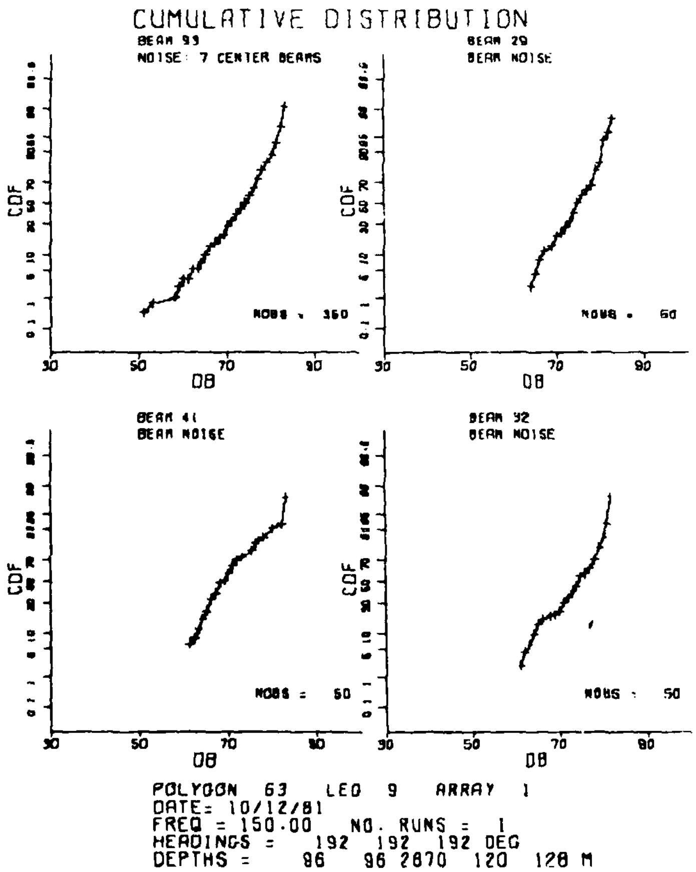


Figure 10. A data-processing output : plots of the cumulative distribution functions of noise levels for selected beams or groups of beams

4.4.2 Cumulative distribution functions

Cumulative distribution functions (CDF) of noise-levels, of the type shown in figure 10, are generated from the time-series by accumulating all the unaveraged (TxBW=1) noise-levels for a single selected beam or for specified groups of beams. For data from the directionality polygons this is done for each analysis frequency for each time-period and also for the combined data set obtained by combining the time-periods of all the legs. The results can thereby be applied to estimating the acoustic performance of a horizontal array on an arbitrary heading.

The time-series of the long statistical tows are processed in the same manner as the time-series of the directionality-polygon legs except that, as explained in Section 4.4.1 above, samples were grouped to give T x BWs of up to 10. The effect of changing the T x BW must be understood in order to interpret the results correctly. This effect can be illustrated by producing listed statistical products (of the type shown in figure 5) for the same data set but for different T x BWs. As an example, figure 11 shows the results of averaging the power of 199 data points from selected aft beams at 500 Hz. The top section of the figure is for no averaging (T x BW=1); the second is for averages of two consecutive points (T x BW=2); the next is for averages of five (T x BW=5), and the bottom is for averages of ten (T x BW=10).

It is seen from figure 11 that as T x BW increases, the intensity of the noise levels increase by about 7 dB at the lowest percentile, increase by about 1 dB at the median, and slightly decrease at the highest percentile. The geometric mean intensity levels are about 2.5 dB higher for a T x BW of 10 than they are for a T x BW of one. These shifts to higher levels with increasing T x BW result from the logarithmic relationship between power and level, in which high values dominate the level of the average power more than they do the average of the individual levels.

The differences in average noise-power level of a fraction of a decibel between lowest and highest T x BWs result from 199 data points being used for the series in the upper section, 198 for the second, 195 for the third, and only 190 for the series in the lowest section. The standard deviations decrease by about 3 dB from the lowest to the highest T x BW.

The remaining parameters also show some effect. The skew has increased, the kurtosis has decreased, and the number-of-runs statistic, the mean-square successive difference statistic, and the Kendall's rank correlation coefficient have all decreased with increased T x BW. Little confidence can be placed in these latter results, however, because of the small number (19) of samples with T x BW=10.

4.4.3 Horizontal directionality estimates from percentile noise levels

Estimates of the horizontal directionality of the noise derived from the 10, 25, 50 (median) percentiles for all azimuths are generated as polar plots, as shown in figure 12. The 50 percentile (median) curve is simply the standard horizontal-directionality curve and is applicable to any array whether it is linear, circular, spherical, random, etc., provided that the beams receive most of their noise power within about 20° of the horizontal. This pattern could simply be convolved with the beam pattern of the array to obtain estimates of median beam levels.

DATE 8/19/1980 SAMPLE SIZE 199
TACTIC 4 LEG 99
ST TIME = 8 8 25 HEADING = 148
FREQUENCY = 300 0 GAIN = 42 0
SOUND SPEED =1496 SIDELOBE = 30 0
LONG= 10 18 N LAT= 49 11
DEPTHS = 82 83 140
WEIGHT = HANN
ARRAY = LOW

BEAM	RHDG	THDG	THDG	BW	10%	25%	MEDIAN	75%	90%	AVG	AVGPR	STDEV	SKEW	KURT	OB	ZRUN	ZMSSD	ZTAU
# AVG = 1																		
32	90 0	238 0	58 0	3 34	46 7	51 5	54 9	57 9	60 1	54 3	56 7	3 16	- 82	73	196	1 295	- 141	1 227
33	91 8	239 8	56 2	3 34	46 7	51 3	54 7	57 4	59 7	53 7	56 1	3 30	-1 23	1 50	197	500	922	1 339
34	93 6	241 6	54 4	3 35	46 5	51 3	54 3	57 5	59 8	53 7	56 1	3 41	-1 00	1 08	197	929	- 717	1 030
35	95 5	243 5	52 5	3 35	43 8	50 9	55 1	57 9	60 2	53 9	56 8	6 07	-1 14	2 01	198	-1 851	-1 370	- 091
36	97 3	245 3	50 7	3 37	47 3	51 5	55 3	58 3	60 9	54 4	57 3	6 09	-1 39	4 23	197	-2 357	-1 939	-1 964
37	99 2	247 2	48 8	3 38	47 9	51 8	55 2	59 0	60 9	55 0	57 5	5 18	- 50	- 14	194	-1 866	-3 104	-2 398
38	101 0	249 0	47 0	3 40	48 6	52 9	55 7	58 6	60 8	55 1	57 3	5 16	-1 12	1 65	198	-2 137	-2 535	-1 803
39	102 9	250 9	45 1	3 42	49 6	52 3	55 7	58 2	60 4	55 0	57 0	4 67	- 74	99	177	1 072	391	- 305
40	104 7	252 7	43 3	3 45	47 4	51 7	54 9	57 7	60 3	54 6	56 7	5 02	- 57	08	198	- 204	- 736	285
41	106 6	254 6	41 4	3 48	47 2	50 5	55 0	58 4	60 4	54 2	56 7	5 39	- 70	46	195	-2 800	-2 187	442
42	108 6	256 6	39 4	3 52	47 2	52 0	55 6	58 7	61 0	54 8	57 3	5 79	-1 17	1 70	195	-1 210	-1 516	342
43	110 5	258 5	37 5	3 56	49 4	52 5	56 3	59 4	61 8	55 7	58 0	5 24	- 98	2 07	196	2 148	593	- 063
44	112 4	260 4	35 6	3 61	46 3	52 1	56 0	60 0	62 3	55 4	59 0	6 49	- 81	1 21	197	- 214	-1 753	-2 006
45	114 4	262 4	33 6	3 67	47 9	51 8	55 9	59 3	63 0	55 9	61 0	6 55	- 17	1 48	198	-2 280	-4 925	-5 186
46	116 5	264 5	31 5	3 73	49 1	52 3	56 3	60 5	64 0	56 7	62 9	6 76	17	98	198	-1 710	-5 443	-6 875
47	118 5	266 5	29 5	3 80	50 1	53 0	57 1	61 0	65 2	57 2	64 0	7 16	- 20	2 55	198	-3 470	-4 405	-5 714
48	120 6	268 6	27 4	3 88	46 8	52 9	57 4	61 1	65 8	57 0	63 8	7 66	- 18	85	194	- 572	-2 625	-4 238
49	122 8	270 8	25 2	3 97	48 7	53 9	57 9	61 4	66 0	57 6	62 6	6 64	- 09	23	195	-1 361	-2 754	-3 913
# AVG = 2																		
32	90 0	238 0	58 0	3 34	51 4	53 3	56 0	57 7	59 4	55 6	56 7	3 38	- 76	65	97	- 713	- 382	1 479
33	91 8	239 8	56 2	3 34	50 8	53 5	55 6	57 1	58 7	55 1	56 1	3 18	- 82	97	98	0 000	1 290	1 652
34	93 6	241 6	54 4	3 35	50 6	52 8	55 1	57 4	58 8	54 8	56 1	3 60	- 75	42	98	- 909	- 717	1 212
35	95 5	243 5	52 5	3 35	49 5	52 8	56 2	57 5	59 6	55 0	56 7	4 34	-1 07	2 13	98	-2 437	-1 620	- 134
36	97 3	245 3	50 7	3 37	50 1	52 8	56 1	58 7	60 3	55 6	57 2	4 12	- 49	- 15	98	-1 625	-3 278	-1 766
37	99 2	247 2	48 8	3 38	50 6	53 3	56 2	58 4	60 9	55 8	57 4	4 10	- 64	17	97	-1 938	-1 606	-1 872
38	101 0	249 0	47 0	3 40	51 8	54 4	56 5	58 4	60 2	56 1	57 3	3 66	-1 34	4 25	97	-2 143	-1 145	-1 717
39	102 9	250 9	45 1	3 42	51 6	54 3	56 6	57 9	59 4	56 0	57 0	3 06	- 53	- 33	98	-1 422	-1 421	0 000
40	104 7	252 7	43 3	3 45	51 4	53 2	55 9	57 6	59 4	55 6	56 7	3 38	- 49	04	98	609	370	872
41	106 6	254 6	41 4	3 48	49 6	53 0	55 8	58 2	59 6	55 4	56 7	3 68	- 37	- 40	98	-1 015	-1 155	586
42	108 6	256 6	39 4	3 52	51 2	54 2	56 7	58 6	60 1	56 1	57 4	3 68	- 95	1 26	98	- 809	-1 645	- 055
43	110 5	258 5	37 5	3 56	50 9	54 8	57 1	59 2	60 6	56 8	58 0	3 47	- 56	- 32	98	004	419	- 258
44	112 4	260 4	35 6	3 61	51 5	54 0	57 0	59 2	61 6	56 8	59 0	4 47	- 21	63	98	- 406	- 729	-1 729
45	114 4	262 4	33 6	3 67	51 6	55 5	56 5	59 3	62 6	57 1	61 0	5 13	76	78	97	-1 122	-4 556	-4 443
46	116 5	264 5	31 5	3 73	51 7	54 3	57 2	60 4	64 7	57 9	62 9	5 61	92	1 01	98	-2 831	-6 337	-6 078
47	118 5	266 5	29 5	3 80	52 5	54 3	58 1	61 1	65 6	58 6	64 0	5 86	94	90	97	-2 75[illegible]	6 098	-4 861
48	120 6	268 6	27 4	3 88	52 6	55 1	58 5	61 3	66 9	59 0	63 9	5 61	96	71	96	-1 847	-5 632	-3 600
49	122 8	270 8	25 2	3 97	52 8	56 0	58 7	61 6	65 4	59 2	62 6	5 12	40	17	98	-2 843	-5 084	-3 821
# AVG = 5																		
32	90 0	238 0	58 0	3 34	53 3	55 1	56 5	57 5	58 6	56 1	56 6	2 56	-1 93	6 17	37	171	-1 142	1 412
33	91 8	239 8	56 2	3 34	53 2	54 3	55 7	57 0	58 1	55 7	56 1	1 98	- 65	87	38	- 987	- 721	1 290
34	93 7	241 7	54 3	3 35	51 7	54 3	55 9	56 8	58 3	55 8	56 1	2 32	- 32	- 50	37	- 162	-1 219	1 032
35	95 5	243 5	52 5	3 36	52 5	54 6	56 1	57 2	58 8	56 0	56 7	2 67	- 26	46	38	-1 316	-2 756	049
36	97 3	245 3	50 7	3 37	52 2	54 2	56 8	58 4	60 2	56 4	57 3	2 83	- 14	-1 77	37	-2 498	-3 728	-1 178
37	99 2	247 2	48 8	3 39	53 1	55 2	56 3	58 3	60 4	56 7	57 5	2 66	05	- 62	37	-2 498	-2 689	-1 595
38	101 0	249 0	47 0	3 41	53 7	54 8	56 7	58 3	59 6	56 7	57 3	2 19	10	-1 87	37	- 830	-2 147	-1 573
39	102 9	250 9	45 1	3 43	53 7	55 1	56 7	57 7	59 1	56 5	57 0	2 12	- 22	-1 05	37	- 496	-1 657	049
40	104 8	252 8	43 2	3 46	53 6	54 3	56 5	57 7	58 5	56 3	56 7	2 02	- 06	-1 43	37	- 496	- 325	1 155
41	106 7	254 7	41 3	3 49	52 4	54 6	56 5	57 6	59 4	56 1	56 8	2 48	- 48	48	37	-1 497	- 650	474
42	108 6	256 6	39 4	3 53	52 9	55 9	57 2	58 4	59 3	56 8	57 4	2 41	- 65	- 07	37	- 830	- 931	194
43	110 5	258 5	37 5	3 57	55 2	56 2	57 7	59 1	59 9	57 6	58 0	1 86	- 37	- 85	35	-1 884	-2 371	- 476
44	112 5	260 5	35 5	3 62	54 3	56 5	57 8	59 2	60 1	57 9	59 0	2 86	67	1 29	38	-2 302	-3 686	-1 788
45	114 5	262 5	33 5	3 67	53 8	55 4	57 4	58 7	62 4	58 1	61 1	4 29	1 46	1 81	38	- 797	-4 646	-3 097
46	116 5	264 5	31 5	3 74	53 6	55 3	57 5	59 5	67 2	58 7	63 0	4 96	1 34	1 62	38	-1 316	-4 529	-4 039
47	118 6	266 6	29 4	3 81	54 4	55 5	57 9	60 4	66 6	59 3	64 1	5 23	1 35	1 52	38	-1 974	-3 285	-3 539
48	120 7	268 7	27 3	3 89	53 7	57 0	58 2	60 8	67 0	59 6	63 9	5 11	1 20	1 14	37	-1 497	-2 381	-2 781
49	122 8	270 8	25 2	3 98	55 7	56 6	59 0	62 0	67 1	60 0	62 6	4 23	94	31	37	- 830	-2 374	-2 875
# AVG = 10																		
32	90 0	238 0	58 0	3 34	54 2	55 5	56 6	57 0	57 6	56 4	56 6	1 38	- 04	70	18	-1 458	-1 147	1 091
33	91 8	239 8	56 2	3 34	53 1	54 8	56 0	56 8	57 4	55 8	56 0	1 46	- 81	4 42	17	-1 242	065	1 091
34	93 6	241 6	54 4	3 35	52 6	55 0	55 4	56 8	57 5	55 7	56 1	1 85	- 38	-1 28	15	- 672	- 766	791
35	95 5	243 5	52 5	3 35	53 2	55 7	56 4	57 2	59 2	56 3	56 8	2 12	- 29	- 68	18	486	-2 087	248
36	97 3	245 3	50 7	3 37	53 8	54 7	56 9	58 6	59 5	56 8	57 3	2 31	- 40	-1 58	18	-1 944	-2 253	- 528
37	99 2	247 2	48 8	3 38	54 0	55 4	56 7	58 7	59 3	57 0	57 5	2 26	- 17	- 66	17	-1 745	-1 433	-1 161
38	101 0	249 0	47 0	3 40	54 4	55 5	56 9	58 2	59 3	56 9	57 2	1 81	12	-1 13	18	-1 944	-1 933	-1 694
39	102 9	250 9	45 1	3 42	54 8	55 3	56 2	57 3	59 0	56 6	56 9	1 34	42	-1 01	18	-1 458	-3 031	- 561
40	104 7	252 7	43 3	3 45	54 7	55 4	56 3	57 4	57 9	56 4	56 7	1 51	23	-5 63	18	-2 430	-1 874	702
41	106 6	254 6	41 4	3 48	53 4	55 2	56 7	57 6	58 4	56 3	56 8	2 08	- 43	- 49	18	-1 458	- 395	387
42	108 6	256 6	39 4	3 52	53 1	56 1	57 6	58 2	58 7	57 0	57 4	1 90	- 79	- 43	18	0 000	- 441	- 284
43	110 5	258 5	37 5	3 56	55 8	56 7	57 7	58 6	59 7	57 7	58 0	1 45	14	-4 51	18	-1 458	-1 249	- 307
44	112 4	260 4	35 6	3 61	55 2	56 1	57 7	58 3	60 3	58 0	59 0	2 52	1 48	3 01	18	-2 430	-2 529	-1 718
45	114 4	262 4	33 6	3 67	54 7	55 7	57 0	58 3	61 5	58 3	61 1	4 08	1 57	1 59	18	0 000	-3 280	-2 316
46	116 5	264 5	31 5	3 73	54 5	55 6	58 1	59 3	68 0	59 1	63 0	5 00	1 24	95	18	- 972	-3 155	-2 904
47	118 5	266 5	29 5	3 80	55 5	56 2	59 1	60 9	65 0	59 9	64 2	5 17	1 21	76	17	- 739	-1 827	-2 526
48	120 6	268 6	27 4	3 88	55 2	57 6	59 3	61 1	66 6	60 4	64 0	4 06	1 23	48	18	486	- 728	-1 834
49	122 8	270 8	25 2	3 97	56 3	57 4	59 1	62 2	66 1	60 8	62 7	3 95	1 04	04	18	486	-1 249	-1 765

Figure 11. The effect of changing the time x bandwidth product in analysing statistical data

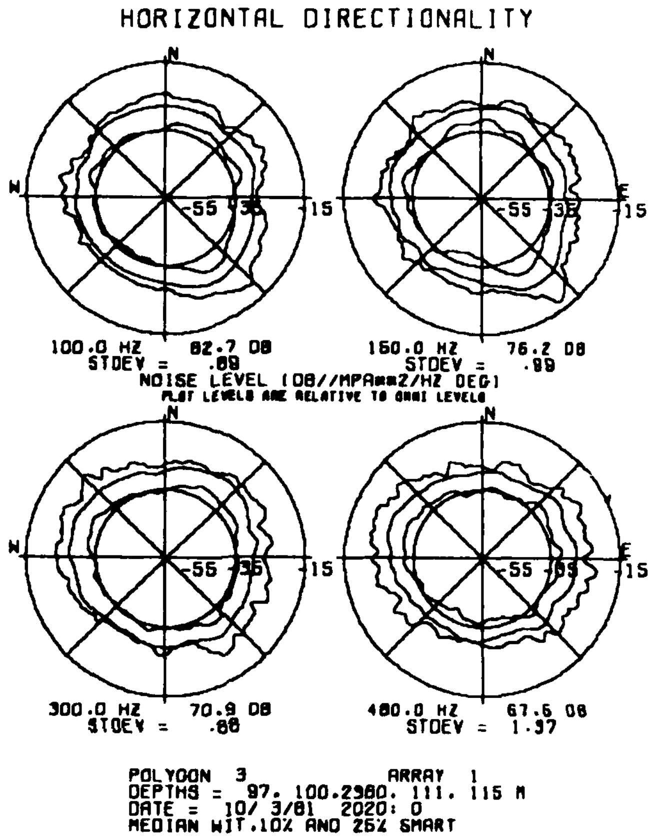


Figure 12. A data-processing output: polar plots of the estimates of horizontal noise directionality (in dB//μPa^2/Hz.°) derived from the 10, 25, 50 (median) percentile noise levels for beams

The 10 and 25 percentile values, on the other hand, cannot be used in such a straighforward manner. The values in the 10 and 25 percentile curves are obtained by the power sum of approximately equal low-level noise from an ambiguous beam pair (the conical beam of the line array intersecting two different azimuthal sectors) and, hence, are valid only for beam pairs. A single unambiguous beam in the direction of the low values would measure an entirely different cumulative distribution function, one with a larger spread. This is not the case in the directions of the high levels, however, since the noise is generally received by a single beam (one of the two azimuthal sectors intersected by the conical beam of the line array). Hence, keeping this one limitation in mind and making the appropriate modifications in the calculation, the 10 and 25 percentile values can be estimated for any array by convolving the beam pattern of the array with the corresponding curve.

4.5 Spatial statistics

The azimuthal anistropy, or spatial granularity, of the ambient noise measured by an array can be expressed quantitatively by plotting its spatial cumulative distribution function, as shown in figure 13. These are called azimuthal anistropy cumulative distribution function (AACDF) plots. AACDF plots are produced for each analysis frequency for selected time-periods from the statistical tows and for the data set obtained by combining the time-periods from each leg of a directionality polygon.

The AACDFs preserve the spatial variability of the noise-field that the horizontal-directionality estimates average out. It is a statistic that characterizes the noise-field by emphasizing both the spatial and the temporal influence of the noise-field on the array. The AACDFs are applicable only to a horizontal line-array. The horizontal-directionality plots (figure 8) described in Section 3.2, on the other hand, are relatively system-independent and the variability in time is averaged out.

The AACDF plots convey a considerable amount of information about the spatial distributions of the noise sources. This information is valuable for predicting the acoustic performance of towed-array systems and for assessing the correctness of the spatial distribution and received noise levels in noise models. The AACDF plots can be used in system-performance estimation by providing spatial distribution functions of the 50 percentile (median) noise levels. This is done for beamwidths (or sector widths) ranging from 0.5° to 10°. Each point on an AACDF plot corresponds to a beamwidth B (read along the vertical axis), a percentage of all azimuth spaces S (read along the horizontal axis), and a median noise-level on the beam L (read along the noise-level curve). The meaning of these three numbers is that a line array with a beamwidth of B° will measure median noise levels of less than L dB on S% of azimuth space. It is a statistical measure of the heights and frequencies of occurrence of the high levels of the noise-field, of the depths and widths of the low regions, and of the distribution of both high and low regions in space. This information is presented in terms of a parameter - the beamwidth - that makes sense for a line array.

The utility of the AACDF for validating noise-models is, perhaps, not as evident as it is for estimating the performance of a towed-array system. One of the first things usually done when validating a model is to compare the measured omnidirectional noise level with the one calculated by the model when the modelled acoustic and noise-source environment is as close to the real one as possible. Next, a comparison between modelled and measured vertical-array output helps to determine whether the physics of acoustic-propagation and noise-source radiation are correctly modelled. Comparisons of horizontal directionality determine the correctness of the gross spatial distributions of the noise-sources. For example, if a shipping lane is on one side of a site but modelled on the opposite side, the modelled omnidirectional levels and vertical directionality can be in agreement with measured values but the horizontal directionality cannot.

When the shipping lane contains a given number of ships, the modelled horizontal directionality will still agree with the measured horizontal directionality whether the model has

(a) the same number of ships with the correct source levels,

(b) ten times as many ships in the same general direction with one-tenth the source level, or

(c) one-tenth the ships with ten times the source level.

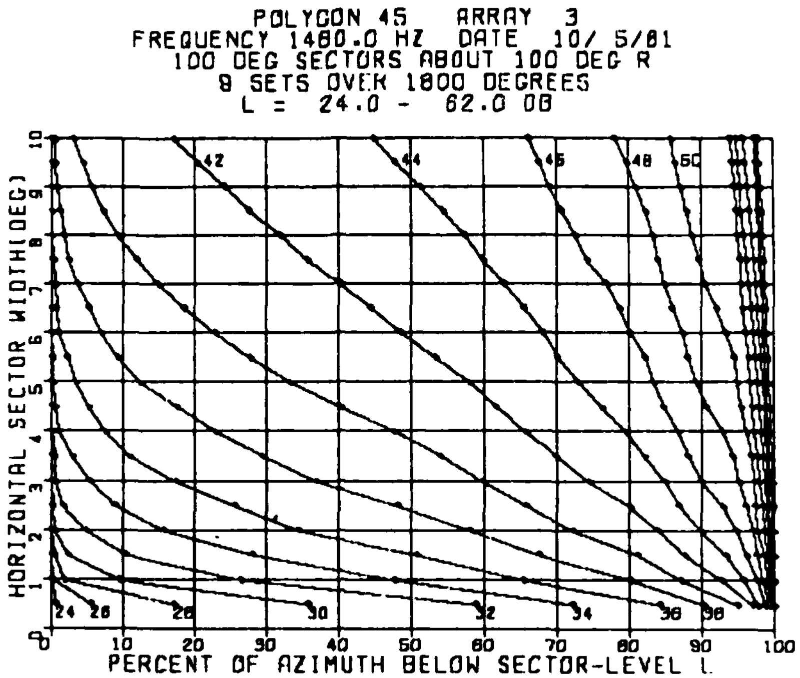


Figure 13. A data-processing output : plots of the azimuthal anistropy cumulative distribution function (AACDF)

The AACDFs for modelled and measured results, however, can agree only if the spatial distribution of ships is correct. This is because the AACDFs are generated from the outputs of beams of varying widths, some that are narrow enough to fit between ships and others that are not. Only when the azimuthal spacing between ships in the model is statistically equal to that which existed during the measurement can the AACDF plots be similar, ie, have the same spacing and slopes of curves; and only when the combination of the average source level and the propagation loss gives the correct received level can the modelled AACDF curves have the same levels as those obtained from measurements. Hence the AACDF is a powerful tool for validating noise-models.

4.6 Array heading rose

Plots that give the S/N gain improvement over broadside performance can be generated from noise roses such as the ones in figure 8, since the average or median array beam-noise for any array heading and beam steering angle in a given detection sector can be estimated from the noise roses. Beam-noise estimates are obtained by convolving the beam patterns of the array with the noise rose. The mean beam-noise levels of the beams with steering angles within the detection sector are averaged, and the resultant is subtracted from the average noise level of a broadside beam in that sector. The result is plotted along the azimuth of the array heading and represents the S/N gain improvement over broadside performance for detection of targets in the detection sector for the array heading along that particular azimuth. When this calculation is carried out for all possible array headings and plotted in polar form, "array heading" plots such as are

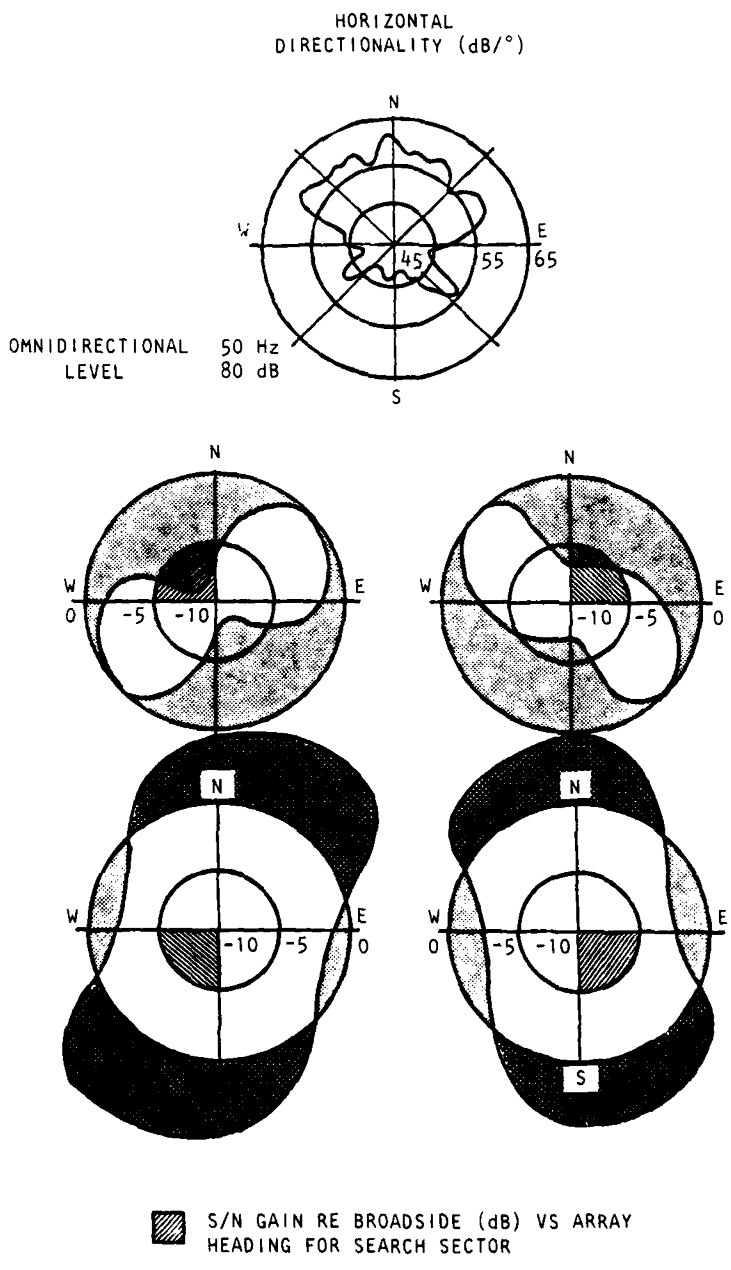


Figure 14. A data-processing output : array heading roses for a noise-field based 10 dB up in the northern half space

illustrated in figure 14 are obtained. Each of these plots is for a different detection quadrant. The specific quadrant for each is denoted by the cross-hatched area. Sectors with other orientations and widths could have been chosen; however, these sectors (the four principal quadrants) are sufficient to illustrate the value of the array heading roses.

The array heading roses in figure 14 correspond to a noise-field which has 10 dB more noise in the northern half-space than in the southern half-space. The points on the curves outside the large circles (0 dB) of the array heading roses correspond to array headings for which there is a S/N gain improvement over broadside performance for detection of targets in the detection sector (cross-hatched sector), while the associated value indicates how many decibels of improvement to expect. The points on the curves inside the large circles (0 dB) correspond to array headings for which the S/N gain performance is degraded relative to broadside performance, while the associated value gives the expected degradation in decibels. By this means these plots aid in the selection of the best array headings for detection.

5. CONCLUSION

This report has described the details and usage of the Towed Array Noise Analysis Package (TANAP). Products proven useful in the quality assessment of towed array data have been shown and explained. Once the quality of data is assured, the same package can be used to analyse the combined beam-noise data to obtain estimates of the horizontal noise directionality. Finally the array heading rose is shown to provide assistance in using a towed array for acoustic signal detection in an azimuthally dependent noise field.

The appendices show how the software is implemented on an IBM 3033.

The package presented here can easily be enhanced by additional products and therefore should provide a solid software foundation for most users of towed acoustic array systems.

REFERENCES

No.	Author	Title
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APPENDIX I

IMPLEMENTATION ON AN IBM 3033 COMPUTER

I.1 Overview

The purpose of these Appendices I to III is to provide basic user documentation for the beam-noise data-processing and reduction system implemented on the IBM 3033 computer. Included herein are brief descriptions of each program and subroutine.

The input data for the processing program are written on disk by a beamformer. The disk contains the beam complex-coefficient data resulting from the double FFT beamforming. The software for this task is called RAW.BEAMS.FORT and is called by RAW.BEAMS.CNTL. Data are calibrated here.

I.2 Program and subroutine relationships

Table I.1 contains an overview of the relationships between the programs used. The ten main programs call subroutines that are both internal and external. The table attempts to indicate this so that the programmer seeking a particular listing will know where to look. Note: Some internal subroutines are used in more than one external subroutine.

I.3 Major Noise Program Segments

The Towed-Array Noise Analysis Packages (TANAP) consists of the following major segments:

(a) RDLMA

RDLMA selectively reads data from a beamformer disc (BEAM) and creates data output for 4 frequencies. The data are formatted in a data file (NSTAT), which is used by the NSTAT programs. ICONT, HYDAT, PHASPL are also output.

(b) HYPLT

Reads HYDAT and BEAM(headers) and plots hydrophone levels for 4 frequencies.

(c) PAPLT

Reads PHASPL and BEAM(headers) and plots hydrophone phases for 4 frequencies.

(d) NSTAT

NSTAT processes the data (NSTAT, ICONT BEAM(headers) files and prints the output in a readable format. During processing, if the option has been selected, the program prepares a data file (CDFST) for use by the Cumulative Distributed Function program. Output to files PLDAT, LONGS, F10, F25, NOISE for later processing.

(e) BEAMPLT

Reads PLDAT and BEAM(headers) and plots beam levels for 4 frequencies.

(f) CDFPL

CDFPL plots the data stored in the data file (CDFST).

(g) WB2

Reads PLDAT, calculates and plots high resolution spatial spectra using the WB^2 technique.

(h) NOISE

NOISE is a noise-ambiguity resolution program that determines the ambient-noise level and the direction from which the noise is coming. The input data for this program are prepared by the NSTAT program and written in the NOISE file. Additional data are found in ICONT and BEAM(headers). As part of the output for this program a data file (AMDAT) is prepared for use by the NOIS7 program. Files L10 and L25 are also output.

(i) NOIS7

NOIS7 is a noise-field directionality plot program that plots the results of the NOISE program. It uses AMDAT as input.

(j) AHROZ

AHROZ uses the AMDAT file to calculate and plot array heading roses for given sectors of search.

I.4 Files Used

The following files are used in TANAP.

FILE	UNIT		FORMAT
LONGS	20	BEAMS FOR LONG STATS RUN	VB A4
NSTAT	21	BEAM OUTPUTS X FREQ X ITERATIONS	VB A4
PLDAT	22	BEAM DATA FOR PLOTTING AND WB^2	FB TEXT
PHASPL	23	HYD AVERAGE PHASE	VB A4
ICONT	24	DATA HEADINGS - USEFUL CONSTANTS	VB A4
F10	25	10 %ILE FOR EACH PERIOD/ALL-NOISE	FB TEXT
F25	26	25 %ILE FOR EACH PERIOD/ALL-NOISE	FB TEXT
R10	27		
R25	28		
L10	29	10 PERCENTILES	VB A4
L25	30	25 PERCENTILES	VB A4
AMDAT	31	PLOTTING DATA FOR NOIS7	VB A4
NOISE	32	VARIABLES AND MEDIAN BEAMS FOR WIT	FB TEXT
HYDAT	33	HYD AVE. MAG.	VB A4
CDFST	34	DATA FOR CDFPL	VB A4
CDFT1	35	DATA FOR CDFPL	VB A4

INPUT BEAMS 10
FROM DJK

APPENDIX II

SIMPLIFIED EXAMPLE OF A RUN PROCEDURE

II.1 Run procedure

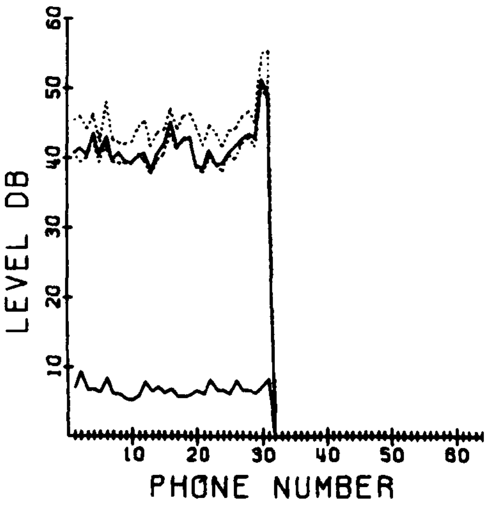
The beam-noise data-processing programs can be run interactively on the IBM 3033 computer. The following example illustrates this and can be used as a guide if the operator responses are modified to reflect the parameters that characterize the type of processing desired.

In the following run example the instructions and answers follow each other on seperative lines. To analyse noise data the following interaction between the operator and computer takes place, commencing with command TANAP:

```
TANAP
TOWED-ARRAY NOISE ANALYSIS PACKAGE (TANAP)
**************************************
LAST CHANGE 20-5-86  BY DJK

PLOT ON:

1 TEKTRONIX 4015 TERMINAL
2 IBM 3278/3279 TERMINAL
3 TEKTRONIX 4663 FLATBED PLOTTER

ENTER OPTION
1

PACKAGE REQUIRES DATA FROM TOWS ON A NUMBER OF HEADINGS
ENTER NUMBER OF LEGS.
5
ENTER TIME CODE FOR LEG NUMBER 1 (DDDHHMM)
2581300
PROCESSING SEQUENCE

1:     RDLMA    READ RAW BEAMS AND SPECTRA. OUTPUT AVERAGE
                BEAMS AND PHONES
2:     HYPLT    PLOT PHONE LEVELS AFTER RDLMA
3:     PAPLT    PLOT PHONE PHASES AFTER RDLMA
4:     NSTAT    TEMPORAL STATISTICS, WRITES NOISE FILE AFTER RDLMA
5:     BEAMPLT  PLOT BEAMS AFTER NSTAT
6:     CDFPL    PLOT CUMULATIVE DISTRIBUTION FUNCTIONS AFTER NSTAT
7:     WB2      WB2 PROCESS OF BEAMS AFTER NSTAT
N:     NO PROCESSING CONTINUE ON
NULL:  NEXT STEP (1)

ENTER PROCESSING STEP
1
ARRAY TO PROCESS (1=SET1 ,2=TACE, 3=  )
?
1
FOR STANDARD ANALYSIS, TYPE 1
?
1
ENTER SAMPLING FREQ
?
1024
 ENTER FFT LENGTH
?
1024
THE ANALYSIS FREQUENCIES ARE  25.0   50.0  100.0  200.0
THE HYDROPHONE TO PROCESS IS  21.0
THE NUMBER OF POINTS TO AVERAGE IS  1
THE NUMBER OF BAD PHONES IS 33
THE TIME WEIGHTING CODE # IS  1
 (1 = UNIFORM  2 = HANN)
THE SPATIAL WEIGHTING CODE # IS  1
IF DATA O.K. TYPE 1
?
1
ENTER SCU GAIN :_
?
0
ENTER 3 ARRAY HEADINGS (EX. 30,42,50,) : _
?
1,1,1
ENTER JULIAN DAY :_
?
```

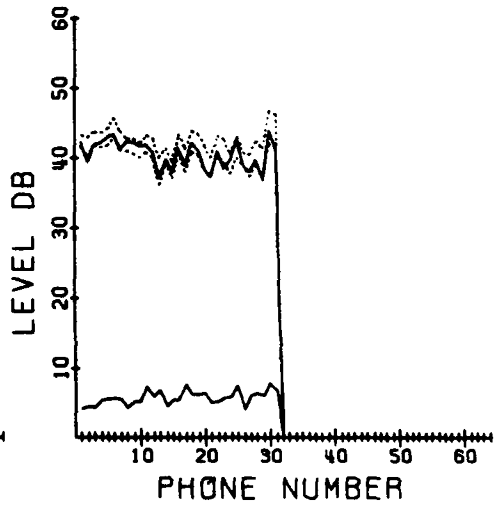
```
250
ENTER 5 DEPTHS IN METERS (EX. 200,232,250,255,270,) : _
?
10,10,10,10,10
ENTER LATITUDE (DEGS,MINS,SEC) :_
?
-31,0,0
ENTER LONGITUDE (DEGS,MINS,SEC) :_
?
151,0,0

 *** MADS PARAMETERS ***
SCU =          0
HEADINGS =            1           1           1
DEPTHS =          10          10          10          10          10
JULIAN DAY =          250
LATITUDE =         -31 DEG             0 MIN
LONGITUDE =         151 DEG             0 MIN
DO YOU WISH TO USE THESE VALUES, Y OR N?
Y

SCU =          0
HEADINGS =            1           1           1
DEPTHS =          10          10          10          10          10
JULIAN DAY =          250
LATITUDE =         -31 DEG             0 MIN
LONGITUDE =         151 DEG             0 MIN

START TIME =  250  13   8  55
 NUMBER OF ITERATIONS =          61
 ENTER ARRAY HEADING (DEG)
?
125
 ENTER SIDELOBE LEVEL IN DB, EQ 30
?
20
 ITA =          61
 IFLCNT =            1
 IFLCNT =            2
 IFLCNT =            3
 IFLCNT =            4
 IFLCNT =            5

 IFLCNT =           50
 IFLCNT =           51
 IFLCNT =           52
 IFLCNT =           53
 IFLCNT =           54
 IFLCNT =           55
 IFLCNT =           56
 IFLCNT =           57
 IFLCNT =           58
 IFLCNT =           59
 IFLCNT =           60
 IFLCNT =           61
PROCESSING SEQUENCE

1:     RDLMA    READ RAW BEAMS AND SPECTRA. OUTPUT AVERAGE
                BEAMS AND PHONES
2:     HYPLT    PLOT PHONE LEVELS AFTER RDLMA
3:     PAPLT    PLOT PHONE PHASES AFTER RDLMA
4:     NSTAT    TEMPORAL STATISTICS, WRITES NOISE FILE AFTER RDLMA
5:     BEAMPLT PLOT BEAMS AFTER NSTAT
6:     CDFPL    PLOT CUMULATIVE DISTRIBUTION FUNCTIONS AFTER NSTAT
7:     WB2      WB2 PROCESS OF BEAMS AFTER NSTAT
N:     NO PROCESSING CONTINUE ON
NULL: NEXT STEP (2)

ENTER PROCESSING STEP
2
 ENTER PLOT REQUEST NUMBER (9 FOR HELP)
?
9

HELP ON THE PLOT REQUEST NUMBER :

 0000 = NO PLOTS
 1111 = ALL PLOTS, ALL PHONES

DIGITS ENTERED MAY BE EITHER '1' OR '0'
4 DIGITS  MUST  BE ENTERED

STARTING FROM THE LEFT, THE DIGITS REPRESENT:
 PRAVG
 MEDIAN
    AVG
  STDEV

 EXAMPLE : THE PLOT REQUEST NUMBER  1011
 WILL GENERATE PLOTS OF THE PHONE DATA FOR AVGPR,AVG AND STDEV

  ENTER PLOT REQUEST NUMBER (9 FOR HELP)
 ?
```

```
START OF PLOT. OPTIONS?

              TOP CURVES:
                    AVGPR..........
                   MEDIAN————
                      AVG..........
    FOR ABSOLUTE LEVELS, ADD 'X' DB TO ABOVE

           BOTTOM CURVES:
                    STDEV————
                          SET1        25813855
```



FREQ = 25.00

X =32.30 DB



FREQ = 50.00

X =35.20 DB

```
PROCESSING SEQUENCE


1:     RDLMA    READ RAW BEAMS AND SPECTRA. OUTPUT AVERAGE
                BEAMS AND PHONES
2:     HVPLT    PLOT PHONE LEVELS AFTER RDLMA
3:     PAPLT    PLOT PHONE PHASES AFTER RDLMA
4:     NSTAT    TEMPORAL STATISTICS, WRITES NOISE FILE AFTER RDLMA
5:     BEAMPLT  PLOT BEAMS AFTER NSTAT
6:     CDFPL    PLOT CUMULATIVE DISTRIBUTION FUNCTIONS AFTER NSTAT
7:     WB2      WB2 PROCESS OF BEAMS AFTER NSTAT
N:     NO PROCESSING CONTINUE ON
NULL:  NEXT STEP (3)

ENTER PROCESSING STEP
```

```
DATE      258 13  8 55     SAMPLE SIZE  61
EVENT SET1                 LEG          1
ST. TIME - 0 0: 0          HEADING -   125
FREQUENCY -    25.0        GAIN -      0.0
SOUND SPEED -1500.         SIDELOBE - 15.0
LONG- 151  0.00 W            LAT-  31  0.00 S
DEPTHS -       100    100    100    100 M.
                 WEIGHT - UNIF
                 ARRAY  -    1
                 # AVG  -    1
```

BEAM	RHDG	THDG	THDG	BW	10%	25%	MEDIAN	75%	90%	AVG	AVGPR	STDEV	SKEW	KURT	OF	ZRUN	ZMSSD	ZTAU	PRDIF
1					48.1	49.9	54.1	58.4	62.0	54.4	57.3	5.37	-0.05	-1.19	58	-0.795	-0.742	0.347	2.9
2					43.6	49.5	52.6	56.7	60.2	52.6	55.8	5.68	-0.13	-1.04	60	-0.521	-1.613	-0.787	3.2
3					43.9	49.6	53.8	57.7	61.2	53.7	56.9	5.66	-0.24	-0.64	60	-0.260	-1.352	-0.595	3.1
4					44.6	47.2	51.8	55.7	59.4	51.6	55.3	5.78	0.16	-0.92	56	-0.809	-1.817	-1.090	3.7
5					43.4	49.1	53.6	57.4	62.0	53.5	57.5	6.37	-0.07	-0.92	56	-1.349	-1.767	0.518	4.0
6					46.3	48.9	53.4	56.7	59.7	53.5	57.3	5.56	0.32	-0.55	58	-2.385	-2.921	1.664	3.8
7					47.0	51.8	55.3	58.6	61.0	55.1	57.9	5.23	-0.23	-0.67	60	-0.521	-0.316	-0.659	2.8
8					47.0	50.1	54.6	57.9	61.1	54.4	57.5	5.59	-0.20	-0.59	58	-1.855	-1.777	0.429	3.1
9					44.9	48.2	52.6	55.3	59.6	52.4	55.5	5.38	0.03	-0.71	58	0.265	-1.962	-0.688	3.1
10					44.6	49.7	53.7	56.3	61.4	53.5	56.5	5.53	-0.29	-0.41	60	0.521	0.070	1.484	3.0
11					48.4	52.2	55.3	59.2	63.0	56.1	59.1	5.38	-0.05	-0.75	58	1.855	0.829	0.145	3.1
12					47.0	50.5	54.2	57.6	60.8	54.1	56.8	5.06	-0.10	-0.76	57	-1.468	-1.018	-1.840	2.6
13					46.4	50.3	55.4	57.9	60.6	54.4	57.0	5.71	-0.80	-0.14	55	0.705	0.254	-0.711	2.6
14					45.6	50.2	53.1	55.7	58.9	52.7	55.2	4.88	-0.12	-0.55	58	-0.795	-0.427	0.997	2.5
15					48.1	50.8	54.3	57.8	60.8	54.5	57.1	5.09	-0.23	-0.73	60	-1.302	-2.087	-1.104	2.6
16					47.9	52.3	55.5	58.5	61.6	55.2	57.6	5.21	-0.62	-0.04	60	-0.781	-1.726	-0.479	2.4
17					45.4	50.1	53.0	56.1	59.8	53.4	56.0	4.86	0.08	-0.71	60	-1.823	-2.705	-0.326	2.6
18					46.1	50.9	55.3	58.9	61.7	55.1	58.6	5.86	-0.08	-0.78	60	-2.344	-0.836	0.204	3.5
19					47.9	52.5	56.8	59.6	62.2	56.3	59.0	5.25	-0.28	-0.95	60	-1.042	-0.597	-1.004	2.7
20					49.1	53.9	56.1	60.0	61.7	56.3	58.5	4.97	-0.55	-0.42	57	-0.666	-1.930	-1.658	2.3
21					54.4	57.4	60.6	63.9	66.0	60.4	63.0	5.10	-0.24	-0.77	60	-1.562	-1.976	-1.926	2.6
22	11.7	136.7	113.3	23.47	60.5	63.4	65.3	69.7	73.5	66.2	68.9	4.90	0.12	-0.64	60	-2.083	-3.940	-2.733	2.7
23	19.1	144.1	105.9	33.49	58.8	61.0	66.5	68.3	74.1	66.0	69.4	5.44	0.34	-0.92	59	-2.494	-4.758	-2.736	3.5
24	35.8	160.8	89.2	17.82	51.4	58.5	63.0	67.0	69.0	62.1	65.4	6.39	-0.65	-0.48	59	-5.121	-4.806	-1.888	3.3
25	45.1	170.1	79.9	14.77	53.9	58.2	62.5	64.5	65.8	61.0	63.3	5.96	-1.60	2.24	59	-2.231	-1.168	-1.401	2.3
26	52.8	177.8	72.2	13.11	53.9	59.1	62.9	65.3	67.9	61.9	64.6	5.64	-0.71	0.01	58	-1.590	-1.809	-2.441	2.7
27	59.8	184.8	65.2	12.07	56.0	59.0	62.4	66.4	70.6	63.0	66.1	5.61	-0.26	-0.42	59	-3.282	-4.661	-2.306	3.1
28	66.3	191.3	58.7	11.39	56.0	60.6	65.5	68.0	70.3	63.6	66.5	6.63	-1.38	1.71	59	-3.807	-3.757	-0.156	2.9
29	72.5	197.5	52.5	10.94	54.3	58.4	64.1	66.0	69.1	62.2	65.0	5.84	-0.82	0.29	59	-2.494	-1.678	2.576	2.8
30	78.4	203.4	46.6	10.64	51.9	57.8	60.8	62.9	66.6	60.5	63.0	5.08	-0.49	-0.13	60	-0.521	-0.730	1.099	2.5
31	84.2	209.2	40.8	10.48	51.3	56.5	60.4	63.0	67.4	59.4	62.2	5.76	-0.65	0.01	60	-0.260	-1.153	-1.611	2.9
32	90.0	215.0	35.0	10.43	50.8	57.7	61.3	63.8	65.5	59.8	62.3	5.84	-1.10	0.37	60	-2.344	-2.982	-0.963	2.4
33	95.8	220.8	29.2	10.48	52.4	56.4	61.0	63.6	68.6	60.7	65.0	6.39	-0.17	0.10	60	-1.042	-3.440	-2.031	4.4
34	101.6	226.6	23.4	10.64	52.3	57.2	60.7	65.9	73.6	62.2	69.7	7.76	0.57	-0.43	60	-1.562	-4.992	-2.713	7.4
35	107.5	232.5	17.5	10.94	53.8	58.0	61.4	65.0	72.1	61.9	68.1	7.08	0.29	0.23	60	-1.562	-4.509	-2.119	6.2
36	113.7	238.7	11.3	11.39	51.2	57.8	59.8	61.8	63.5	59.0	60.8	4.75	-1.03	0.44	59	0.659	1.067	1.011	1.9
37	120.2	245.2	4.8	12.07	49.4	54.4	60.5	63.7	66.4	59.1	62.5	6.32	-0.56	-0.23	58	-1.325	-2.747	-2.520	3.4
38	127.2	252.2	357.8	13.11	54.0	58.6	62.0	64.3	67.1	61.4	63.3	4.39	-0.37	-1.37	59	1.185	0.299	-0.886	1.9

APPENDIX III

PROGRAMS AND SUBROUTINES USED IN THE TOWED ARRAY BEAM-NOISE ANALYSIS SOFTWARE

III.1 Statistical calculations, programs and subroutines

NSTAT Program, See Appendix I.3.

R3LMA Subroutine, interactively sets up parameters for NSTAT. Selectively reads data in NSTAT file for NSTAT program to print out statistics tables.

RDLMA Program, See Appendix I.3.

STAT2 Subroutine, performs statistical calculations on all beams including the virtual beams.

STAT5 Subroutine, calculates Spearman's rank correlation coefficients.

MEDAM Subroutines, calculates median value of input data.

MEDAN Subroutine, slightly different from MEDAM.

CLOZE Subroutine called by MEDAM and MEDAN, finds the index of the element closest to the given ranked position.

SZTAU Subroutine, calculates Kendall's Test for correlation.

GROUP Subroutine, groups data and computes cumulative distribution function.

JRANK Subroutine, places the rank at an integer vector in another integer vector. The original vector in unchanged.

STAT6 Subroutine, computes cumulative distribution function.

PROB Subroutine, calculates azimuthal arisotropic cumulative distribution function.

PROBL Subroutine, plots azimuthal anisotropy cumulative distribution function.

SETUP Subroutine used in probability plots.

HYPLT Program, See Appendix I.3.

BEAMPLT Program, plots average power, dB average, median standard deviation and power differences of the beam noise.

PAPLT Program, see Appendix I.3.

CDFPL Program, see Appendix I.3.

III.2 WIT related programs and subroutines

NOISE Program, driver for function involving, WIT. "How many frequencies"? "How many legs"? "Enter number of bad phones". Use median or dB average, what beams to skip, AACDF's, etc.

NOIS1 Subroutine, setup data and run parameters for the WIT algorithm.

NOIS2 Subroutine, driver for WIT algorithm.

CONV Subroutine, performs convolution for WIT.

MSQD Subroutine, performs testing and field modification for WIT algorithm.

NOIS5 Subroutine, calculates bounds (HIBAR and LOBAR) used in subroutine MSQD.

BWCAL Subroutine, modifies beam widths and beam center angles for use by WIT. Contains correction factor for less than 64 hydrophones.

SMART Subroutine to calculate SMART results.

SMSEG Subroutine, sets up data and calls SMART to get 10 and 25 percentile directionalities.

NOIS6 Subroutine, writes noise field from WIT and beam data to plot file.

NOIS7 Program, see Appendix I.3.

FLDPL Subroutine, plots the noise field from WIT on polar axes.

LEGPL Subroutine, plots the leg beam noise data on polar axes.

III.3 WB^2 related programs and subroutines

WB2 Program, see Appendix I.3.

SMUZ Subroutine, a data smoother.

CNVLV Subroutine, does convolution.

BRESP Subroutine, calculates beam responses.

OREST Subroutine, calculates first estimate of noise field.

NWDAT Subroutine, reads data for plotting WB^2 from file PLDAT.

WITPL Subroutines, plots WB^2 result.

AHROZ Program, see Appendix I.3.

AMRES Subroutine, reads data from AMDAT for AHROZ.

BPLOP Subroutine plots noise and array heading roses.

III.4 Set up and general purpose subroutines

DDNAD Interactively requests nonacoustic data, ie SCU gain, array heading, Julian day, array depths, latitude, and longitude and prints them out.

BWTST Requests interactive input of frequency array type, array heading, shading and sound velocity.

BHDX Calculates the beam numbers of the useable beams for the FFT beamformers.

R2LMA	Subroutine, gets hydrophones data. Unscrambles the beams. Calculates median hydrophone.
WEIGT	Function, computes inverse Hann shading coefficients for 40 hydrophones and a 64 point FFT.
RDBEM	Subroutine to read beam data called by STAT5.
ASINE	Function calculates, the arc sine function and range of result from 90 to +90 to 0 to 180°.
BWST	Calculates beam widths and centres.
FRAME	Subroutine used in plotting.
LINE	Subroutine, draws line, used in all plotting subroutines.
XYPLT	Subroutine, draws a line.

DISTRIBUTION

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Director, Weapons Systems Research Laboratory	1
Chief, Maritime Systems Division	1
Chief, Combat Systems Division	1
Head, Marine Studies	1
Head, Sea Experiments Group	1
Head, Underwater Detection Group	1
Head, Signal Processing and Classification Group	1
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17 SUMMARY OR ABSTRACT
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A software package for onboard acoustic data-processing and the statistical analysis of array beam-noise has been implemented on an IBM 3033 computer system. The package both assesses data quality and measures the noise-field's statistical characteristics and directionality. Many of the outputs are sufficiently general to have application to other types of data or to satisfy other objectives. The various outputs are described and illustrated by results from measurements of the ambient noise by a towed array. A simplified run procedure is included to facilitate the use of the software package by the analyst.

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